THESES ON MECHANICAL AND INSTRUMENTAL ENGINEERING

Synergy-Based Approach to Design of the Interdisciplinary Systems

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Declaration: Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any degree or examination.

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Publications of doctoral research results and division of research between co-authors

The results of research have been published in the proceedings of the leading Scandinavian and worldwide scientific forums. Only the last publication (9th in the present list) has not been published yet, but it was accepted for publication in August 2005.

The results of research have been published in the following proceedings:

1. Reedik V., Kaljas F., Tähemaa T., On Evaluation the Trends in Mechatronic Systems Design, Proceedings of the Second Nationational DAAAM Conference in Estonia SCIENCE´96, Tallinn, Estonia, 1997, pp. 89-93.

   An analysis of design methodologies for mechatronic systems design. Material collected by T. Tähemaa and F. Kaljas in equal parts, written under supervision of Professor Emeritus V. Reedik.

2. F. Kaljas, V. Reedik, On Synergistic Aspects in Integrated Product Development of Mechatronic Systems, Proc. of 6th Mechatronics Forum International Conference MECHATRONICS’98, Skövde, Sweden, September 9-11, 1998, PERGAMON, pp. 513-516. (peer-reviewed).

   Reasoning of the need for the use of the synergy-based approach in interdisciplinary systems design. Written by F. Kaljas, supervised by Professor Emeritus V. Reedik.

3. Tähemaa, T., Kaljas F., Martin A. and Reedik V., Indispositions at Interdisciplinary Systems Design, Proceedings of the 3rd International DAAAM Conference “Industrial Engineering – New Challenges to the SME, Tallinn, April 25-27, 2002, TTU Publications, 2002, pp. 66-69.

   An analysis of the usability of synergy-based aspects in interdisciplinary systems design. Written by T. Tähemaa, F. Kaljas and A. Martin in equal parts, supervised by Professor Emeritus V. Reedik.

4. Vain J., Kuusik A. and Kaljas F., Safety Verification of Degrading Mechatronic Systems, Proceedings of the Fourth International Conference on Machine Automation: Human-Friendly Reliable Mechatronics, ICMA’02, September 11-13, 2002, TUT Publications, Tampere, Finland, 2002, pp. 615-622. (peer-reviewed).

   A theoretical approach and a case study of the evaluation of product performance quality. Case study was compiled by F. Kaljas.

5. Tähemaa T., Kaljas F. and Reedik V., Assurance of Synergy and Competitive Reliability at Mechatronics Systems Design, Proceedings of the 2nd IFAC Conference on Mechatronic Systems, December 9-11, 2002, Berkeley, California, USA, Elsevier Science, Oxford, 2002, pp.871-876. (peer-reviewed).

   The analysis of the essence of the positive and negative synergy and the prognosis of permissible negative synergy of a new product based on competitiveness on the market. Written by T. Tähemaa and F. Kaljas in equal parts, supervised by Professor Emeritus V. Reedik.

6. Kaljas F., Martin A., Tähemaa T. and Reedik V., Synergy Dimension at the Design of Interdisciplinary Systems, Proceedings of International Symposium on Machine Design OST'2003, June 5-6, 2003, Oulun Yliopisto, Oulu, Finland, 2003, pp. 138-147.

   A preliminary proposal for the framework of synergy-based design of interdisciplinary systems. Written by F. Kaljas, A. Martin and T. Tähemaa in equal parts, supervised by Professor Emeritus V. Reedik.

7. Kaljas F., Källo R. and Reedik V., Realities in Interdisciplinary Systems Design, Proceedings of International Conference NordDesign 2004, TUT Publications, Tampere, Finland, 2004, pp. 251 – 259. (peer-reviewed).

   An analysis of synergy problems in engineering design teamwork. Written by F. Kaljas and R. Källo, R. Källo´s Master's Thesis supervised by F. Kaljas, assisted by Professor Emeritus V. Reedik.

8. Kaljas F., Källo R. and Reedik V., Human Aspects at Design of Mechatronic Systems, Proceedings of the 9th Mechatronic Forum International Conference, Atilim University Publications, Ankara, Turkey, 2004, pp. 147-157. (peer-reviewed).

   A summary of the analysis of synergy-based shortcomings in the design and application of equipment control and factory automation systems. Written by F. Kaljas and R. Källo, R. Källo´s Master's Thesis supervised by Kaljas, assisted by Professor Emeritus V. Reedik.

9. Kaljas F. and Reedik V., On Using the DSM Technology Approach to Synergy-Based Design of Interdisciplinary Systems, Proceedings of the 15th Conference on Engineering Design ICED ´05, to be held August 15-18, 2005 in Melbourne, Australia (peer-reviewed and accepted for publication).

   The completed framework for synergy-based design of an interdisciplinary system with the case study. Written by F. Kaljas, supervised by Professor Emeritus V. Reedik

INTRODUCTION

Increased integration of different technologies in new products with improved performance and marketing power due to the exploitation of the best features of allied technologies has been an ever-growing tendency during the last decades. At the same time, the design of interdisciplinary systems integrating different technologies is a complicated activity as no suitable design metatools are stillavailable, allowing technology-related design tools integration. Around the beginning of this century, the research community of engineering design reached a somewhat confusing conviction that classical prescriptive engineering design methodologies are the past. It is obvious that engineering design is not a pure technical problem any more but a complex activity, involving artefacts, people, tools, processes, organizations and conditions of the real economic environment (Blessing, 2003; Hansen & Andreasen, 2003; Persson et al., 2003). In this context, it is not realistic to expect unshakeable methods of interdisciplinary systems design as the intervention of market effects in product development methodologies is steadily growing. It seems that the term design methodology is necessary in a wider interpretation context – as a generic model of activities, integrating design methods and procedures that are necessary for attaining the goal.

In the launched race between research groups to fill this gap it seems that one of the possibilities to solve this situation is to involve a new paradigm – the synergy-based approach to design. The synergy-based approach developed at Tallinn University of Technology (TUT) makes it possible to bring design parameters, market conditions, human factors, reliability problems, etc under one umbrella. The research of synergy-based approach to interdisciplinary systems design was proposed by the Department of Machinery of TUT under the supervision of Prof. V. Reedik. The first to introduce the synergy-based approach to mechatronic systems´ design on an international research forum were Reedik, Tähemaa and Kaljas in 1998 (Tähemaa & Reedik 1998; Kaljas & Reedik 1998). But the synergy-based physical and logical optimization principles were used already in early the 1970 in the studies of high-accuracy pneumatic interruptible jet sensors and in the development of a high-performance pneumo-hydraulic relay servo.

The synergy-based approach to interdisciplinary systems design based on the compensation of mutual weaknesses and amplification of useful effects between the allied technologies seems to be a good possibility to solve the problem. Synergy is treated here as an effect of suitable integration when the whole is more than the sum of its parts. The optimistic approach to that possibility is based on the fact that there is a limited number of products available where the synergy of allied technologies is to some extent achieved. But this synergy has still been achieved based on intuition or occasion rather than resulting from a systematic approach. However, the existence of outstanding synergistic products implies that some guidelines for the successful movement in that direction must exist. The doctoral study of T. Tähemaa (Tähemaa, 2002), was a substantial step on this way. He analyzed an extensive database of mechatronic office equipment performance and proved the reality of the positive and negative synergy concepts. The essence of the effects of negative synergy in an infant mortality period of the brand new product was thoroughly studied and a methodology for prognosis of the negative synergy was developed. However, synergy is not only a technical problem, it involves also synergy between product development team members, resulting in a successful or failed product. There is still a substantial “white“ area – how to separate the human and technical aspects on the negative synergy side and to reach to the development of the design methodologies. The present doctoral research attempts to fill this gap.

The aim of this research is to develop a possibly complete concept of the use of the synergy-based approach in the design of interdisciplinary products and systems to attain the maximum synergy of the allied technologies performance.

To attain this goal, four basic problems have to be solved:

1) to conduct a thorough analysis of the existing engineering design methodologies to form a suitable basis for synergy-based methodologies for interdisciplinary systems design;
2) to create a complete concept of synergy-based treatment of interdisciplinary systems design parameters in the positive and negative synergy context;
3) to conduct experimental research to find the synergy-based aspects of engineering activities, based on a comprehensive analysis of the database containing shortcomings related to equipment control and factory automation systems design and application;
4) to develop a strategy and a methododical framework for the synergy-based design of interdisciplinary systems and verify its applicability.

All of these research topics need to be given a more detailed interpretation.

The first task has to be solved because in the previously described situation in the field of engineering design methodologies no clear vision of how to design a competitive product for the market. It is clear that consideration regarding the market conditions and human factors are essential. Therefore, first of all, it is necessary to study the existing engineering design methodologies and find their hidden potential to manage the complicated situations in interdisciplinary systems design.

The second topic is necessary to provide a comprehensive picture from the still fragmented synergy characteristics and to add color to the still existing ”white” or unexplored areas. As a result of the doctoral study of T. Tähemaa (Tähemaa, 2002), it was proved that positive and negative synergy are the objective parameters in the design of a mechatronic product and system. This research will focus on the evaluation of quantitative characteristics of the positive synergy and on the development of the tools for the treatment of synergy characteristics in interdisciplinary systems design, including the human and market environment aspects.

The third research topics involves the most complicated task to be solved – to separate the human and technical aspects in the effects of the negative synergy. In other words, it is necessary to study thoroughly the reasoning of "bad" engineering, separating its effects of engineering activities and unsuitability of allied technologies. The task is based on the of real situation that requires the development of a large database of integration experience in different technologies into equipment control and factory automation systems.

The three topics above are integrated in the fourth – to summarize the results of all the topics in order to propose a framework methodology for the synergy-based design of interdisciplinary systems. It seems necessary to form some hybrid area between descriptive and prescriptive approaches to design. The follow-up of the development of the high accuracy pneumatic positioning system, recommended by Bosch Rexroth AG as an effective application task for this doctoral research, may serve as a touchstone for the development of synergy-based design methodologies.

The present doctoral research is not a separate study but rather an independent part of the activities of a larger research group (see Fig. 1).

The present doctoral research tends to be superficial and diffusive, thus distancing from the classical strict structure of a thesis. The integrated topics described above also emphasize the generalistic pattern of this thesis. To avoid of this kind critique, a justification for the present structure is to be provided. By and large, the studies are based on a unique database of human and technical shortcomings compiled in the framework of the preparation stage. In fact, the above determined structure of the thesis, i.e. first, the separation of human and technical aspects in the so-called "bad" engineering was required. As a result, it ensures that the value of the findings be verified and trustworthy.

The research presented in this thesis has been carried out at the Department of Machinery of TUT. The continuous support of the Department to my postgraduate studies is gratefully acknowledged. I would like to thank also Estonian Science Foundation for financial support during 2002 – 2004 by grant 5168.

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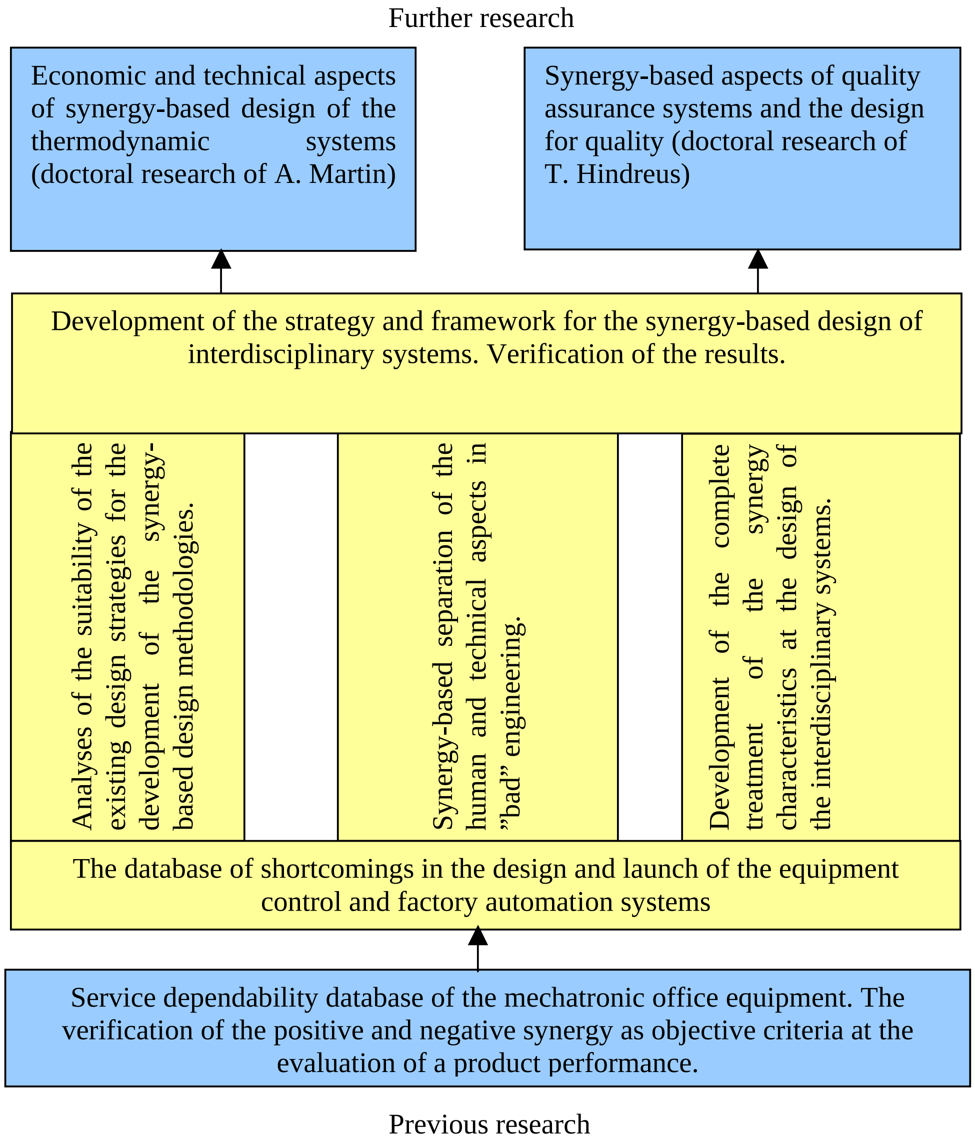

Economic and technical aspects of synergy-based design of the thermodynamic systems (doctoral research of A. Martin)

Synergy-based aspects of quality assurance systems and the design for quality (doctoral research of T. Hindreus)

Development of the strategy and framework for the synergy-based design of interdisciplinary systems. Verification of the results.

Analyses of the suitability of the existing design strategies for the development of the synergy-based design methodologies.

Synergy-based separation of the human and technical aspects in ”bad” engineering.

Development of the complete treatment of the synergy characteristics at the design of the interdisciplinary systems.

The database of shortcomings in the design and launch of the equipment control and factory automation systems

Service dependability database of the mechatronic office equipment. The verification of the positive and negative synergy as objective criteria at the evaluation of a product performance.

Figure 1. Generic structure of the thesis

I would also thank my colleagues at Bosch Rexroth Oy, especially Kalle Tuohimaa.

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1 SURVEY OF FEASIBILITY FOR INTEGRATING METHODOLOGIES IN INTERDISCIPLINARY SYSTEMS DESIGN

1.1 Overview of design strategies and decision-making algorithms

There are two substantial reasons to provide this survey. Firstly, it is necessary to select from approaches and elements in existing design methodologies for allied technologies those that can be used in the development of the metamethodologies, to achieve a higher level and broaden the perspective to the integration of these technologies into interdisciplinary systems. Secondly, it is necessary to establish the most suitable tools for the organization of the management of synergy-based design information during the whole design process.

Increased integration of different technologies in new products with improved functionality and marketing power has been an ever-growing tendency during the last decades. As a result, different technologies in the field of engineering have become more intertwined and so it is of great importance to find generic guidelines for the management of the growing integration. Despite these developments, the integration of the design methodologies of interdisciplinary systems is far behind the wave of integration of the allied technologies itself. It is obvious that this integration cannot be treated as a simple summing of the allied technologies but as a way of compensating their mutual weaknesses and amplifying the synergy of integration. Synergy here is treated as useful collaboration between allied technologies where the summary effect is higher than the sum of its parts. In technique it is obligatory to know the preconditions at the integration of different technologies into the allied system to gain the synergy of their collaboration. It is generally accepted that synergy in the integration of mechanics, electronics and software is the only real key for entering the highly competitive market of mechatronic products where the reduction of weight, energy consumption and life-cycle cost of a new product with higher quality, safety and responsibility at better dynamic performance are decisive success factors (Buur, 1990; Salminen & Verho, 1992).

Interdisciplinary systems design is not only a pure technical problem, as design decisions depend substantially on product customization and also on the competition situation on the market. The ever-growing competition on the markets has caused the need for radical cuts in interdisciplinary product development time. The more frequent alternating of product models on the market and therefore the ever-limiting feedback information about their reliability and durability have put the industry into a difficult position. In this situation, industry has to change the approach to the design for reliability and to involve customers in the follow-up product development. Despite this product quality continues to be the key driver of the product development process. In this context, the role of human faults and mistakes in product development emerges and it is still a practically “white” area in the research field. The reason for it seems to be the confidentiality of such kind of information and the difficulties in separating technical and human effects.

In the 1970s, the world market of mechatronic products appeared to be full and industry arrived at the truth that in hard competition for world market shares it is possible to survive only by radical cuts in product development time. Thus, different schemes for speeding up product innovation were developed, having parallel, integrated and concurrent patterns of marketing, design, production and financing. In the 1990s when the mega-competition age started, the conflict between the growing demands for functionality and quality of products at a lower price became the everyday reality in companies and continual renewing of a company’s managing structure, work organization and product development tools were required to grant the sustainability of the company. The situation described above has had a strong impact on the development of engineering design methodologies on all three levels: design philosophy, theory of technical systems and special design methodologies.

The majority of the authors of methodological publications of engineering design support the strictly formulated prescriptive product design methodologies, differing mainly in the iterations structure in the staged design process: sequential (Pahl & Beitz, 1996; Suh, 1990; Hubka & Eder, 1988), cascade (Cooper, 2001; McConnel, 1996; Smith & Reinertsen, 1992; Urich & Eppinger, 2000), or spiral (Boehm & Bose , 1994; Hekmatpour & Ince, 1988; Gilb, 1988). Without any doubt these methodologies have provided basic guidelines at the design of multiple successful monotechnological products. It seems that the sequential approach is more wide spread in mechanical engineering design, cascade in more complicated interdisciplinary systems and the spiral approach at software systems design (Unger, 2003). The minority of authors support more free descriptive approach to the design based on free problem-solving strategies and case studies (Bröhl, 1995; Birkhofer et al., 2001; Sauer et al., 2002, Sauer et al., 2003).

The main goal of the research in the interdisciplinary systems design is to propose an approach helping to attain the maximum synergy of allied technologies. To solve this task, a suitable background framework of engineering design methodologies has to be found, enabling one to involve synergy metrics into the design process. It should be pointed out that the achievement of the maximum synergy is limited by market conditions as maximum synergy costs are usually an order higher than market prices would allow. In view of classical design strategies (sequential, cascade or spiral approaches), they do not include special tools for integrating different technologies. In the engineering design methodologies the main shortage is that they concentrate only on structural and behavioral aspects of the designed artifacts, not taking into account human aspects and market environment. In other words, most of the classical engineering design methods are purely academic. But the effective product development process cannot be built up without taking into account the real situation in the industry and markets. A successful separation of human and technical aspects in the design of interdisciplinary systems opens up new possibilities to synergy-based design, allowing one to cope with the deficiencies outlined.

A more promising way to integrate different technologies is through the systems theory, allowing for intertechnology-based development. If you look at the design methodologies on three levels – problem-solving in general, the synthesis of technical systems and the total activity of product development, then the first and the last are really more universal, not necessarily strongly related to any of allied systems (Andreasen, 1993). If you analyze the level of synthesis of technical systems, then you can be convinced that the systems theory and systems thinking seems to be the only possible basis for mechatronic systems design (Buur, 1990; Salminen & Verho, 1992; Ringstad, 1997; Andreasen, 1993). This general strategy applied for products´ design is based on the design domains´ philosophy (Andreasen, 1980) where the design process consists of the succession – process, function, organ and parts domains with a lot of possible feedback. It is clear that the functional structure of a mechatronic system must be described in terms of states and transitions from one state to another. Transformation function is described by the continuous flow of material, energy and information and state functional structures by changes in the mode of functioning. The question how to solve the growing conflict between transformation and state functional structures in the same design models is critical.

The truth is that in the modern highly competitive environment only those interdisciplinary products are successful, in the development of which the synergy of integration of allied technologies has been achieved. Despite an intensive research of interdisciplinary systems design, modeling and simulation, the power of the interdisciplinary approach does not seem to have been used in full extent so far. For further development of the integrating design tools, the Theory of Design Domains seems to be most suitable. During the study of existing design methodologies, an improper conclusion has been drawn – is it possible to allocate the enormous multiplicity of design tasks to the prescriptive methodologies or may these design tools to be as adaptive to these different conditions.

1.2 Information management at the integration of different technologies

In this context it is appropriate to classify product design methodologies into three categories: using parallel, from time to time or continuous treatment of allied technologies information. Differences between these approaches, are shown in Fig. 2. The structure of the decision-making stage is based on the Theory of Design Domains (Andreasen, 1980) but it seems that there is a additional need for some

QDF-type matrix at the beginning of design domains (Fagerström et al., 2002), that is appropriate to name as market relations domain. Similar decision-making steps are typical for most design methodologies but are named differently, for example, task clarifying, concept design, embodiment design, layout design etc. (Boehm & Bose, 1994; McConnel, 1996; Pahl & Beitz, 1996; VDI 2221, 1993; Gilb, 1988).

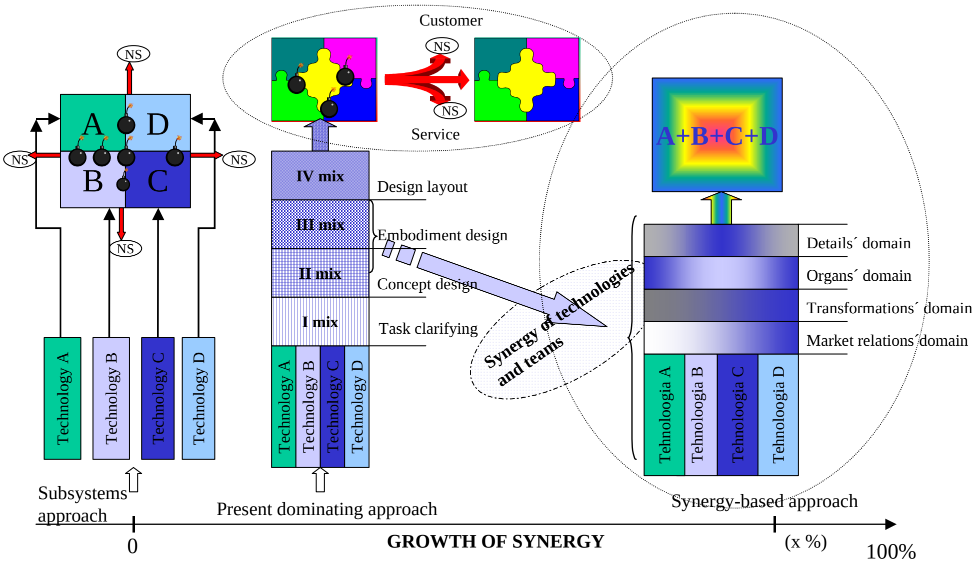


Figure 2. Strategies for the use of integrated technologies information

The widespread practice in mechatronic engineering, integrating mechanics, electronics and information technology at the end of the last century was characterized by a subsystem-based approach (see Fig. 2), by which integrated systems are compiled from homogenous technology subsystems without a real demand for the development of a certain technology for their closer integration (Wikander & Törngren 1998). However, in that case no attention is paid to the most important issues – the incompatibility of different technologies and the amplification of useful effects between the technologies, involved in interdisciplinary systems. The new VDI 2206 guidelines for mechatronic systems design appear much closer to the solving of the integration task are set up (Gausemeier & Moehringer, 2003; VDI 2206, 2002).

It has been a trully difficult task to move from the subsystems approach to synergistic design, as it is still prevalently an uncovered research area. The task of designing an interdisciplinary system for synergy would be much simpler if the design methodologies of its allied technologies were similar, but unfortunately, it is not so. One of the most comprehensive comparative analysis of mechanical, electronic and software design systems has been provided by J. Buur (Buur 1990). When he compared such methodological characteristics as functions, concept design, concept realization, design modeling and design methods, they appeared to be quite different. The same comparative analysis of design methods was repeated by the author about a decade later (Kaljas, 1999). As a result, no signs of coming closer to a solution were found, in fact, it was even vice versa.

The VDI 2206 (Grausemeier & Moehringer, 2003) guidelines are a typical approach to integrating recent achievements in mechatronic systems design (Bröhl, 1995; Sauer et al., 2002; Birkhofer et al., 2001). This approach belongs to a hybrid (from time to time) use of integrated technologies information. This conclusion is based on the fact that the VDI 2206 approach assumes periodical differentiation and integration of information of allied technologies. The VDI 2206 guidelines are based on the V-type model, allowing top-down decomposition and down-up integration. When moving from more general levels to more detailed ones, it resembles the spiral approach.

In the present context, an important question may arise – where to allocate the remarkable number of product modeling and simulation methodologies. The approach mentioned has rather an analysis – optimization rather than a synthesis character, at the same time, it allows to enfold the dynamic behaviour of interdisciplinary system components (Calderon, 2000). But the same technology-dependent pattern is cognitive also in modeling. The general type modeling software (Matlab, Simulink, etc.) is really technology-independent, however, it is too superficial to introduce synergy-based interactions of system elements (Aarino, 1999). At the same time, special modeling softwares are too technology-specific, having no tools for integration (Krastel & Anderl, 2001). One of the promising tools for technologies integration is the metamodel approach of the chromosome model proposed by Hallin (Hallin et al., 2003), integrating systems theory approach.

Thus, the growing need for the evaluation of the complexity parameters of the products is evident (Salminen & Verho, 2000). The growing complexity makes the management of product components and chunks interactions so intricate that a capable decomposing framework for their analysis is needed. An appropriate tool for managing the complexity seems to be the Design Structure Matrix (DSM) developed by Steward (Steward 1981). The DSM technology developed by Eppinger (Pimmler & Eppinger, 1994) is a suitable environment for this. The philosophy of the DSM seems to be the most convenient environment for interdisciplinary systems design, having three steps of decomposition–integration. The first step documents the decomposition of the product into components. The second one enables one to identify the interactions between the components and, finally, the third step is to cluster the components into a system around their integration challenges defined by the network of interactions. Eppinger has used this approach for the analysis of the product architecture of large-scale engineering systems and has proved that it is a powerful tool for a complexity analysis on the task level by structuring them into sequential, parallel and coupled tasks and to use optimal iteration cycles (Eppinger & Salminen, 2001). Thus, an outstanding capability of the matrix methodology is that it is giving continuous support for decision-making during the whole design process.

In conclusion it is clear that there is a growing need for a new integrating approach for interdisciplinary systems design. This approach has to give a possibility to bring together all the complicated issues of interdisciplinary systems design and to create a complete picture of all realities in the design process. The author of the present thesis believes that one possible solution of the present situation may consist in the synergistic approach to the integration of the different allied technologies. Figure 2 shows the efficiency of the synergy-based approach marked on synergy axes as x%, justified by the fact that optimal synergy level is determined by competitively on the market.

In summary, it is possible to set up the following main requirement for synergy-based interdisciplinary systems design methodologies – all the interactions between the subsystems and their elements must be continuously visible and available to evaluate the performance of the whole system.

1.3 Conclusions of Chapter 1

1. The increased integration of different technologies in new products with improved performance and marketing power due to the best features of allied technologies has been an ever-growing tendency during the last decades. A thorough analysis of the existing engineering design methodologies has proved that all allied technologies have their specific design tools built up on different bases and do not show a trend for closer integration. Consequently, in the design of interdisciplinary products and systems it is reasonable to use a more general or meta-approach. The synergy-based approach seems to be a good possibility to solve this problem. Synergy here is treated as an effect between a suitable integration when the whole is more than the sum of its parts.
2. It seems that stringent prescriptive methodologies are not purposeful for the solution of the intuition-based creative problems and the synthesis of decision-making algorithms based on teamwork synergy and market situation. The present engineering design methods are profoundly academic, focusing only on the structural and behavioral aspects of the artifacts designed. The synergy-based approach to design makes it possible to recover the deficiencies observed.
3. It is appropriate to build a synergy-based methodology for interdisciplinary systems design on the basis of the systems theory approach and to use the decision-making algorithm and stage structure of the Theory of Design Domains. This is a capable tool for synthesizing the complicated systems in a technology-independent manner, moving in the decision-making

environment from abstract to concrete and undetailed to detailed direction in every stage of the synergy-based integration.

4. The Design Structure Matrixes technology that makes it possible to describe synergy-based interaction between systems components and design processes is a suitable basis for the information management of allied technologies. The transformation of the matrixes makes it possible to involve scheduling and time dimensions into the design processes.

2. SYNERGY DIMENSION AT DESIGN OF THE INTERDISCIPLINARY SYSTEMS

2.1 Synergy-based approach to design realities

The introductory part described the reasons urging that a new paradigm – a synergy-based design- be created. The analysis in the previous chapter has led to a conviction that synergy-based design is the only real possibility of solving the allied technologies integration problems. In the movement toward the synergy-based design philosophy, first, 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” refers to the situation when 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. Thus, there is “something” that makes integration successful and it is usually called a “positive” synergy. However, sometimes we witness an unfortunate integration because allied technologies or procedures are unsuitable to accomplish the planned task. For symmetry, it is appropriate to call it a “negative” synergy. Some critics ignore the term “negative synergy” as they are used to think that synergy is always of the positive meaning. However, in the technical literature the term “positive” and “negative” results are quite common (Ballard, 2001). The essence of the synergistic approach to interdisciplinary systems design is shown in Fig. 3.

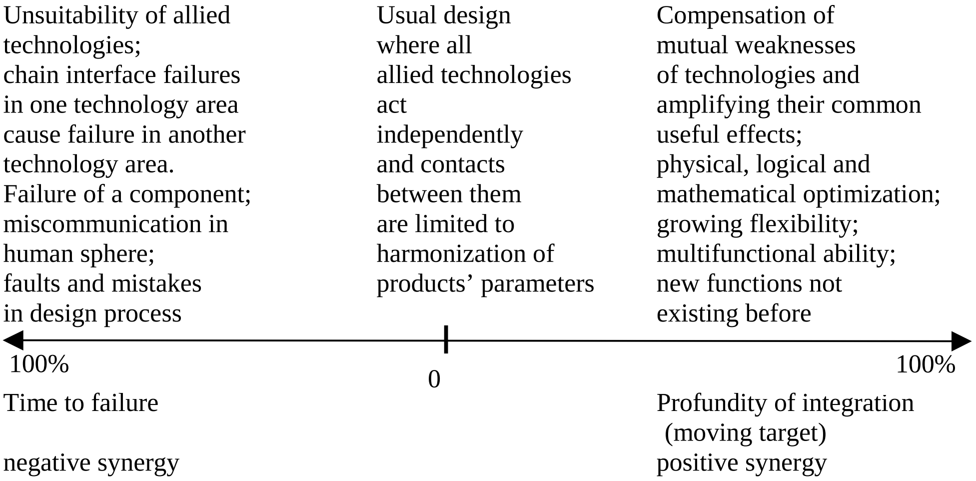


Figure 3. Positive and negative synergy deployment

To apprehend better the philosophy of synergy integration we can draw parallels from the social system. As a result of normal education and human development, the so-called ordinary people grow up who are able to operate successfully in society and at work on their professional level. However, there is a small group of people whose natural talent has been powered by subsequent education and training giving them outstanding capabilities for fine arts, science, sport, etc.

One of the requirements for moving ahead in synergy-based engineering design methodologies is to use quantitative characteristics of synergy. It is impossible to compare the performance of the product and systems designed without the metrics of benchmarking. Several systems of the evaluation of the positive synergy have been put to test (Tähemaa, 2002), but it means that the evaluation of synergy in percentage is the most universal and essential. The scale of measuring may start from 0 for conditional interdisciplinary synergy-free product. For the evaluation of the positive synergy it is possible to use a relative parametrical scale based on the benchmarking of similar products on the market. The maximum value on the positive side of this scale means reaching the maximum synergy (100%) where everything has been squeezed out of the allied physical processes. It is impossible to say where the real maximum is, as it means the fixation of the end of any development and further research. The validity of such an approach has the same value as repeating unsuccessful proposals of human limits in sport. On the negative synergy side, some reasons for spring-up of the negative synergy effects are listed that make product performance ineffective or stop its functioning. As an example, the negative synergy level introduced into a system by the unprofessional design of the sliding pair may in the process of increasing wear move on the scale left up to full breakdown that marks 100% negative synergy. 100% negative synergy corresponds also to the situation where an unprofessionally designed product or system does not function at all. It is obvious that to attain the maximum synergy of interdisciplinary systems it is necessary to take into account all substantial interfaces between the components and modules of the system carrying the features of different technologies. The basic idea here is the development of design methodologies of interdisciplinary systems as filtering systems having a capability of allowing through and amplifing engenders of positive synergy and impeding the entrance of the negative synergy effects.

2.2 Ways of attaining the positive synergy and pressing down the negative synergy

Generic foundation of the positive synergy is optimization in its wider interpretation. The roots of the synergy-based design are hidden in the value engineering and robust design. During the whole history of engineering design one can notice the striving for the optimization of the result. A typical example of optimization in engineering design is the family of design tools “Design for X”. The simplest way is logical optimization, always used in the design process. In complicated situations, outside the brains’ seizure, we have to apply mathematical tools. However, the success of the analytical approach also depends on the level of knowledge about the real physical processes in the product and perfectness of a logically developed structure. Thus, it is possible to assert that there are three allied ways of optimization – physical, logical and analytical. In reality, all of these three approaches complement each other, calling forth total synergy of performance. The precondition for granting physical synergy at the interaction of different technologies is understanding the gist of integrated processes on such a level that it is fully possible to control these processes. However, it is also possible to achieve the decisive effect of synergy allocation by logical integration of the known physical effects. Mathematical modeling and optimization are powerful tools to save time and resources at experimental research and at the verification of the behaviour of systems (Vain & Küttner, 2001; Vain et al., 2002). The art of success lies in a rational use of the three ways to achive a higher synergy of integration.

In any case, it is not possible to ignore negative synergy facts due to their insidious action and a tendency to occur again. Negative synergy is closely related to the reliability characteristics of the system and it reveals itself mostly in the infant mortality period of a new product's life cycle. The classical understanding of system reliability is not very suitable for interdisciplinary systems as besides mono-technology failures there are also combined failures or effects of incompatibility on the allied technologies interfaces. It means that in addition to the ordinary intra-technology reliability characteristics, their interfaces reliability should be taken into account (Tähemaa & Reedik, 2001). In this context, also the relationship between component reliability and system reliability must be understood. A particular component may fail as a direct result of a physical reason, or it may fail as a result of a chain failure of another component of the system. In the synergy context, reliability can be treated as a process where the synergy of the operation of components is gradually reducing (wear, emission, etc) and stops functioning when the accumulated negative synergy reaches its final value –100%. Chain failure can be treated as the negative synergy between allied technologies.

In order to find up the roots of negative synergy in the framework of his doctoral research, T. Tähemaa completed a five-year service statistics database for non-safety-critical mechatronic office equipment. (Tähemaa & Reedik, 2001). Four generations of office machines were under observation. The database consists of up to 3,000 service actions solved in 2000 work hours with the total turnover of 350,000 EUR. The analysis of the service database has proved that the negative synergy phenomenon dominates in the infant mortality period of a brand new model. Thus, it is evident that failures from incompatibility of allied technologies or negative synergy prolong the infant mortality period of a brand new product compared to a mature product. For the brand new product, the infant mortality period extends approximately to 1/3 of its lifetime, for a mature product it is between 1/4 - 1/5. The share of interface failures from all service actions (adjusting, cleaning, mono-technology failures, user errors) was 24%, this fact cannot be neglected. Due to the gradual upgrading of the product, negative synergy effects are decreasing and the infant mortality period is closing to a mature one. It is obvious that by the replacement of the failed components it is possible to restore the initial synergy level.

Thus, it is extremely important to find tools for pressing down the influence of the negative synergy and the basic idea here is the development of design methodologies of interdisciplinary systems having a capability of impeding the spreading of negative synergy effects caused by the incompatibility of allied technologies. Another important key for reducing the negative synergy is to increase the team's core competence and the synergy of teamwork during the design process. Wrong decisions of judgement and lack of skills were previously considered as technical problems and were taken as a generic basis of the negative synergy. An analysis of the database of shortcomings of equipment and factory automation compiled in framework of the present doctoral research allows for providing a solution to this problem (see Chapter 3).

2.3 Universality of synergy-based approach

So far the present thesis has concentrated mainly on the technical aspects of synergy at different allied technologies integration into the interdisciplinary products and systems. But the design of interdisciplinary systems is not only a pure technical problem, but is intertwined with the competitive situation on the market and the requirement to adapt the product with market needs. The ever-growing competition on the markets has caused the need for radical cuts in product development time. The more frequent alternating of the product models on the market and therefore limited feedback information about their reliability and durability have put the industry into a difficult position. In this situation, industry is forced to change the approach to the design for reliability and quality. Due to the fast interchange of models it is impossible to provide comprehensive reliability testing. Thus, during the infant mortality of the new product it is inevitable to involve the customer and service system into the follow-up product development. Today's methodologies of mechatronic systems design for reliability are developed at a very high level due to the needs of aviation, nuclear technology, space and military techniques. In the so-called safety-critical systems it is necessary to grant extraordinary reliability and therefore the cost has been a second-rate matter. In general machinery, non-safety-critical systems dominate and the vouch for unshakable reliability raises the cost of products so high that it is impossible to sell them. The main difficulties related to the synergy-based treatments of the quality dimension imply both a perceptual and a technical concept (Robotham & Guldbrandsen, 2000). In this context, quality and reliability problems for non-safety-critical products have changed into market driven categories. Movement toward the high level of reliability and therefore low service dependability brings about an increased product cost and difficulties in sales. If the dependability is too high, the amount of repairs at the warranty time increased and the service net must be expanded. Thus, the reputation of the company will suffer.

In this context, the relations between synergy and quality emerge. The goals and nature of synergy and quality assurance are quite close to each other and it is clear that all that is made to increase synergy brings along improved quality (Hindreus & Reedik, 2002). In this context, the Design Structure Matrixes (DSM) approach was used to study quality-synergy interactions. The quality-synergy matrix view was built up according to the DSM technology rules, having 20 indicators of quality and synergy. The indicators were grouped in such a way that the first eight represent the classical pillars of the TQM system. The next six indicators have been classified into the category of products quality deployment and the last six into the pure synergy category. The quality and synergy correlation proposed earlier is quite impressive: on the medium level 67%, of which 10% can be classified as a strong correlation. However, product quality continues to be a key driving force of the product development process and more attention has to be paid to improving the upstream activities of the product development process.

It is obvious that only a well-founded prognosis of optimal reliability makes it possible to select the one from alternative design solutions that is by price/reliability ratio competitive on the market (Tähemaa & Reedik, 2001). Each new performance quality of the product is usually synergy-based and may be taken as the next step in competitiveness. If this new product is successful on the market – the positive synergy is born and the market distribution is changed. The quality assurance depends a great deal on the organizational side of product development or, to be more exact, on the quality of human performance as synergy between the members of the product development team, resulting in a successful or failed product. There is still a substantial “white“ area – how to separate the human and technical aspects on the negative synergy side, which will be discussed in the next chapter.

Moving ahead in this analysis it is clear that success in the teamwork strongly depends on the synergy in thinking and the action of the team members. In the same way effective work of a single person depends substantially on his / her inner communication synergy. Thus, there is another problem to be solved – how to use the synergy characteristics to be integrated in the framework of design methodology. In Chapter 1, a conclusion was reached that the DSM technology is a suitable basis of synergy-based design methodologies. It is because this approach involves the description of all interactions between system components in a synergy-based manner. Thus, the processing of the matrixes can be built up on saving its synergy bases. The scheduling of the design processes makes it possible to involve teamwork synergy characteristics and thus it appears to open a door to a complete synergy-based design. In summary, it is possible to argue that synergy is the universal criterion for the evaluation of technical, marketing and human behavior aspects in the design process.

2.4 Conclusions of Chapter 2

1. It was proved that the positive and negative synergy are objective realities suitable for the evaluation of the interdisciplinary products and systems performance. In the present research, the previous mechatronic approach was extended to larger interdisciplinary systems used in equipment-control and factory automation. For the quantitative evaluation of the synergy, the per cent metrics is a most favourable, where the 0-point denotes the “synergy-free” artefact. In the present thesis, the detailed cognitative level implies a way of increasing the positive synergy and suppress the negative synergy effect.
2. It was shown that the positive synergy at the integration of allied technologies into interdisciplinary systems is attainable by a rational integration of the physical, logical and mathematical optimization. The maximum value on the positive side of the synergy scale means reaching the maximum synergy closer to 100%, where everything has been squeezed out of the allied physical processes. It is impossible to say where the real maximum is, as it means defining the end of any development and further research. As raising the synergy level needs remarkable resources, the optimal synergy level is determined by market situation.
3. A conviction was reached that it is not possible to ignore processes on the negative direction of the scale due to their insidious action and a tendency to occur again. It is shown that negative synergy is closely related to the reliability characteristics of the systems and it reveals itself mostly in the infant mortality period of a new product’s life cycle. It was pointed out that the classical understanding of a system’s reliability is not very suitable for interdisciplinary systems as besides mono-technology failures there are also combined failures or effects of incompatibility of the allied technologies interfaces (up to 24% of all failures). In the synergy context reliability can be treated as a process where the synergy of the operation of components is gradually reducing (wear, emission, etc.) and stops functioning when accumulating negative synergy reaches its extreme value (-100%).
4. Despite detailed research conducted to find the essence of the negative synergy separating human and technical aspects has not been successful. Unclarity in this substantial problem makes it is impossible to develop design methodologies and to press down the negative synergy effects caused by “bad” engineering.
5. In the context of the development of the design methodologies for interdisciplinary systems, the synergy is a universal indicator. By help of synergy it is possible to express all the substantial parameters used in the design process, including quality, reliability, human factors, and competitiveness.

3. SYNERGY-BASED ANALYSIS OF HUMAN AND TECHNICAL SHORTCOMINGS AT INTERDISCIPLINARY SYSTEMS DESIGN AND APPLICATION

3.1 Research methodology and database

As described in previous Chapters, the last “white” area to be covered in the synergy-based design methodologies of the interdisciplinary systems is the separation of the human and technical aspects in the negative synergy effects. Wrong decisions of judgment and lack of skills were previously considered as technical problems and were taken as a generic basis of the negative synergy. It is really difficult to distinguish in “bad” engineering the effects from the unsuitability of the integration of the allied technologies from those effects where the lack of competence and faults or mistakes at design are the real reasons. The only way out is to analyze the experience gained from real systems design and application. Unfortunately, the published fragmented and casual data do not help the synergy-based treatment of the human shortcomings. Usually those data are used only as the inner information in companies. The key problem here is to compile a representative database to solve this problem.

In the present research the whole range of interdisciplinary systems is conditionally divided into three categories: consumer products, equipment control and large factory automation systems. Earlier, a similar research was provided for mechatronic consumer products - the office machines (Tähemaa, 2002). But this research did not allow one to study the human aspects at design as the objective of research was to study negative synergy effects occurring in equipment use during the infant mortality period. In the present research, this approach was enlarged to the field of larger interdisciplinary systems, focusing on human shortcomings in the design and application of the systems developed. During the last four years, a unique database of human and technical shortcomings was compiled, comprising more than 13,000 equipment and five factory automation control systems design and commissioning cases. Although the analysis of the problems at the launch of control systems is extremely useful, it is at the same time a very sensible 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 world-wide known strong contributors in the field of automation.

The possible outcome of the data analysis is statistical and so it is appropriate to keep apart the results for equipment control and factory automation systems. In addition in equipment control systems, an interesting possibility of differentiating the so-called “old” and “new” technologies emerges. In factory automation systems, it is purposeful to distinguish shortcomings during the virtual and real testing. However, first, it is necessary to specify the terms used in the further analysis. In this database, all the shortcomings (see Fig. 4) occurring at the design and launch of the interdisciplinary systems were classified into human faults F, human mistakes M, and technical problems T. Faults are the wrong decisions that have no justification. Misunderstandings in the communication between the client and the design team or between design team members belong to fault category F1. All the shortcomings connected with negligence belong to the category of faults F2. Faults F1 may be treated as a result of negative synergy in teamwork and F2 as negative synergy in a person's inner communication.

Mistakes are of a far more complicated nature. Wrong decisions M1, caused by lack of competence at synergy-based integration of different technologies belong to this category. Another category of mistakes M2 is conditional, is caused by unknown matters at that moment of time to be studied in the further research or during the system's testing or use. A special category here is technical problems T where a component is working poorly or does not function at all. The reason for it may be the arrival on the market of a brand-new product with its infant mortality negative synergy effects.

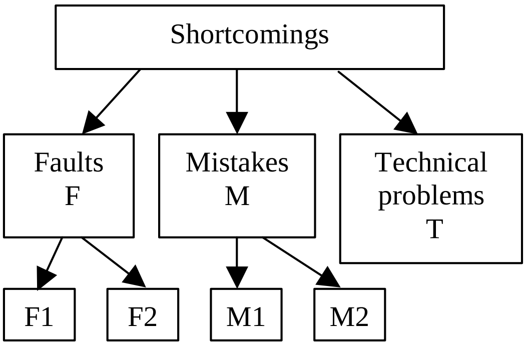


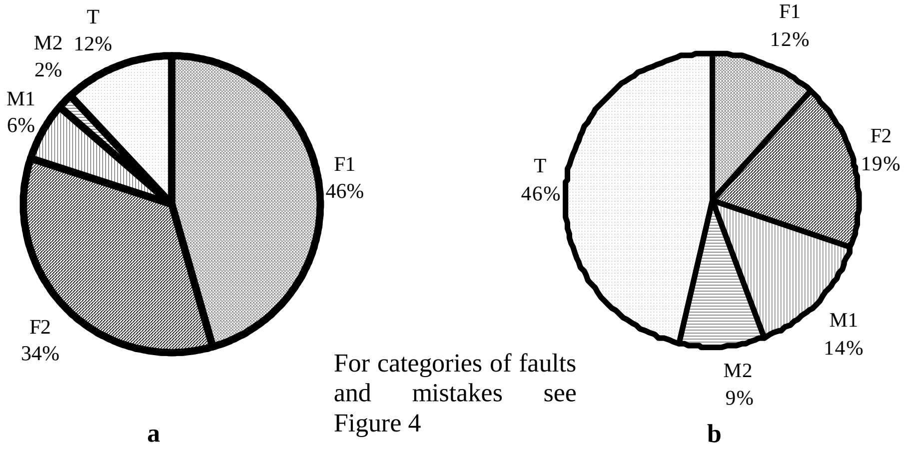
Figure 4. Classification of shortcomings at the launch of a new automation system

Thus in summary, it is obvious that nearly all shortcomings in the design and application process of a interdisciplinary system can be treated as synergy-based. It should be added here, that in a complete analysis another detailed classification level was used, but it does not give additional information for synergy-based approach and therefore is not commented in the present theses.

3.2 Analysis of shortcomings

In equipment control systems, the cooperation between the customer and the systems application team is so closely intertwined that only summarized shortcomings analysis is possible. Even in those conditions quite an interesting difference between well-established and comparatively new technologies can be observed. Fig. 5,a shows a statistical analysis of human shortcomings for equipment control systems design and application for such a well-established area as electropneumatics/hydraulics systems with programmable logic controllers on the top of hierarchy. At first sight, the dominating share of faults is conspicuous. In the category of F1, most of the faults are caused by wrong orders as the client and the designer may have a different and sometimes fragmented picture about the control system and its parameters. In the category of faults F2, a typical reason is the order of an unsuitable apparatus or apparatus with wrong parameters. A comparatively low share of technical problems can be explained by the maturity of the components used. In Fig. 5,b, the analysis of shortcomings for equipment control systems is presented where a comparatively new technology - servo drives & control is used. On the same balance of faults F1/F2, the dominating share of technical problems T can be noticed. The reason to it seems to be that the new components are also still in the infant mortality period.

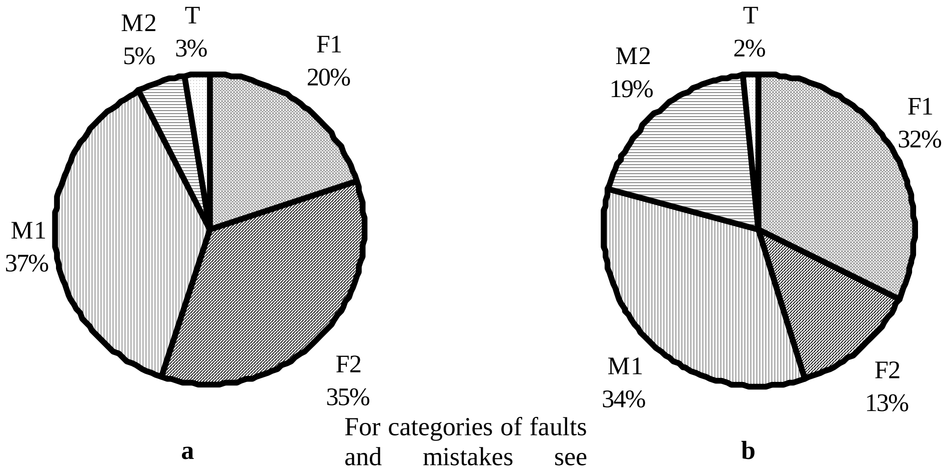
Now a more detailed description of the mistakes will be given as they are almost common for both levels of technologies. Typical mistakes in the category of M1 are caused by the lack of the team's core competence. As an example, when applying the positioning system it may happen that the theoretical limit of positioning accuracy appears to be much lower under real external conditions. This category of mistakes includes the case when a system's parameters are in the limits of low dynamics, but far out of the conditions of high dynamics. It is reasonable to allocate all the mistakes of category M2 when it appears that it is possible to establish or to tune the exact parameters of the controlled processes only during a later experimental study. The dominating share of the technical problems T is caused by the infant mortality of the brand new or low quality of the mature components. Sometimes a new apparatus is used that appears later on the market or its parameters are on a lower level than declared.



For categories of faults and mistakes see Figure 4

Figure 5. Analysis of human shortcomings for equipment control systems design and application

For factory automation it is appropriate to provide an analysis of shortcomings for two levels during virtual factory acceptance test (FAT) at systems' supplier and in the process of the commissioning step where the real automation system is tested. The length of the commissioning stage period ranges from a few weeks to several months, depending on the scope of the system delivered. In Fig. 6,a presents the statistical analysis of the human shortcomings or statistics for factory automation systems design and application on the FAT level. As it is seen, the faults are strongly dominating here. Faults from mutual misunderstandings F1 are usually clarified during the FAT. Typical faults of category F1 have been born on the grounds of inadequate initial information, differences in understanding components functioning, later proposals for user interface, etc. In the category of F2, comparatively simple faults are dominating: input-output ports or logical functions are entangled, some signals have an opposite effect, wrong information is used, important alarm has been forgotten, etc. In general, all of these faults can usually be easily corrected by changes in software. On the mistakes' side in the category of M1, the incompetence of the client and the design team is dominating. Usual mistakes of the same type are: the use of unsuitable components or models, incorrect calculations, wrong integration of interrelated signals, incorrect imagination about tuning parameters, etc. The share of mistakes M2 is trivial. As the tests are still virtual, only some mistakes related to the application of a new software may occur.



For categories of faults and mistakes see Figure 4

Figure 6. Human shortcomings analysis for factory automation systems design and application

Fig. 6,b shows the shortcomings analysis for the commissioning stage of factory automation. On the faults side the share of F1 is still high and it seems that FAT has been superficial and only part of the faults have been successfully eliminated. However, the real situation is not so gloomy, as at this stage, all the proposals of final operators and also innovative solutions worked out during the testing are introduced. In the real working process, all the shortcomings in communication are revealed and also the absence of necessary sensors, blockings and alarms is found. In the first plan in the category of faults F2, faults in cabling and installation of sensors and drives appear.

On the mistakes side in the category of M1 again, mainly incompetence in the main technological process is dominating. In real testing, all the wrong decisions in the choosing process parameters and logic are found. The changes to be introduced into the system are mainly concerned with the requests of final users (operators). In the category of mistakes M2, tuning and regulation are dominating, as the preset parameters prognosis may appear to be wrong for the real conditions. Sometimes additional units for a smoother functioning of control systems or machines are necessary. To eliminate these mistakes, some new knowledge about the real processes and automation system functioning are required.

3.3 Ways of reducing human faults and mistakes

The purpose of every automation activity is to offer a suitable, flexible and reliable system meeting the client's needs and expectations and to help them to increase the productivity and efficiency of business. A survey of the engineers and managers in the automation field has shown that these extra costs of removal of the shortcomings can attain up to 5-10% of the system's cost that is, in reality, quite an impressive. It is necessary to add also that the losses from the production not received are usually much bigger. All the results of the experimental research described above are somewhat alarming, as misunderstandings and negligence that can be easily avoided in some cases form up to half of all shortcomings. Furthermore, it should be pointed out that the lack of competence of the design team is too dominating.

The most important problem here is how to improve the synergy in teamwork to avoid faults of the category of F1 based on mutual communication. Nowadays information technology is offering improved online communication possibilities for dispersed teams and in some time the share of this type of faults has to decrease. On this background, the inadequate impact of the FAT is clearly seen and it seems that it is appropriate to enlarge the representation of the customer's technical personnel on this level. Otherwise, it happens that a lot of faults on the system's operational level move from FAT to the commissioning area. It is absolutely necessary to run a dated database to grant that all changes made in the systems reach all the people involved. It is also possible to reduce the most human casual negligence faults F2 by checking the design process continuously using special design tools helping to uncover the most common deficiencies. At the same time, upgrading of the professional level of the personnel and taking unpopular measures to increase the responsibility of the personnel are appropriate. However, there is also another side to the problem – typical overload of application engineers being basis of speedy and incorrect decisions. On the mistakes M1 side, most of the problems are caused by lack of competence. To the newcomers to the automation area it is recommended to rely more strongly on consulting service in the beginning. Special attention must be paid to the continuous upgrading of the personnel. It is most difficult to reduce the mistakes belonging to the category of M2 as they depend on the state-of-art of the development of the used technology. Numerous tuning and regulation activities occur inevitably at the commissioning stage. During the start-up of the systems new unknown matters having effect on production may occur. In summary, it is necessary to say that the key for reducing negative synergy effects is to increase the synergy of teamwork at the design and application stages and the team's overall core competence. The value of the present research is a true and an average overview about realities of human aspects in the field of "bad" engineering. This analysis also refers to a approach of how to solve the problems of human aspects in a synergy-based manner.

3.4 Conclusions of Chapter 3

1. Today's engineering design methodologies cannot be perfect if we neglect the human factor as it is a substantial agent in the timing of the product development process and introducing quality into product performance. Despite detailed research to find the essence of the negative synergy so far separating of human and technical aspects has not been successful. Thus, the clarification of this substantial problem is essential in the development of design methodologies to press down the negative synergy effects. One of the main research targets of the present thesis is the experimental research to clear up the synergy-based aspect of engineering activities.
2. A unique database of shortcomings concerning equipment control and factory automation systems makes it possible to separate the human factors from pure technical reasons in the negative synergy effects. In addition, the faults in teamwork and individual communication and mistakes from team incompetence and immature technology were distinguished. Quite an interesting difference between well-established and comparatively new technologies can be observed. It helps to remove a curtain from the essence of so-called "bad" engineering and to take measures to improve the design process.
3. It was shown that the role of human factors in the formation of the negative synergy effects may be treated as a synergy-based manner – as lack of synergy in the teamwork or in person's inner communication.
4. The results of the analysis of human shortcomings at the design and application of the equipment control and factory automation systems are somewhat alarming, as misunderstanding and negligence that can be easily avoided form in some cases up to half of all shortcomings. Also, it should be pointed out that the lack of competence of the design team is too dominating. It was shown that the key to reducing the negative synergy effects is to

increase the synergy of teamwork at the design and application stages and the team’s overall core competence.

5. Resulting from the research of the human aspects, the idea of adaptive engineering design tool is taking shape, making it possible to synthesize the rational roadmap of attaining the goal proceeding from the team’s competence and expert knowledge.

4. SYNERGY-BASED FRAMEWORK FOR INTERDISCIPLINARY SYSTEMS DESIGN

4.1 Integration of the Design Structure Matrixes (DSM) technology and Theory of Design Domains

In Chapter 1 a conviction was reached that the most suitable environment for design of the interdisciplinary systems seems to be integration of DSM technology and Theory of Design Domains. The DSM technology was developed by Steward (Steward, 1981) and due to the outstanding capabilities of describing the interactions of systems' components, the use of the matrix methods has become more and more popular (Erixon, 1998; Pimmler & Eppinger, 1994; Suh, 1990; Clarkson et al., 2001; Malmqvist, 2001; Morelli et al., 1995). Eppinger has used this approach for the analysis of the product architecture of large-scale engineering systems and complex interactions between product components, their design process and supporting organizations (Eppinger et al., 1994). From the point of view of the synergy-based design of interdisciplinary systems, it is suitable to involve also the systems engineering approach to make it possible to control the advancing of the design process in the 3-dimensional design space: undetailed-detailed, abstract-concrete and by steps of the realization of the artefact. A suitable basis for it seems to be the Theory of Design Domains proposed by Andreasen (Andreasen, 1980). This theory is based on applying three views of the product – transformations', organs' and parts' domains encompassing of substantial classes of structural definitions and behaviours of artefact (Hansen & Andreasen, 2001). This design concept is realized through horizontal and vertical causality chains (Hubka & Eder, 1984). The Domains Theory makes it possible to link the engineering designer's considerations about the interdisciplinary system (delivering effects for the purposeful transformation) via considerations about organs (creating effects) to considerations about the parts being produced and assembled (Andreasen, 1993).

It seems that by integrating the technology of Design Structure Matrixes technology and the Theory of Design Domains it is possible to create a good design environment to make it possible to involve time and human competence dimensions in the design methodology (Cho & Eppinger, 2001). In Fig. 7, the essence of the proposed generic model for interdisciplinary products and systems design is proposed. 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-market conditions and human aspects. In the added domain of market analysis, matrix 1 presents the activity-type DSM that allows one to take into account the marketing trends and to initiate the synergy-based activities in the firm's product strategy planning so that the developed products should be competitive on the market. Matrix 2 in the transformations' domain is parameter-based DSM that gives an algorithm for the design process and opens a possibility to reach to the optimal synergy level and performance of the product designed (Hansen & Andreasen, 2001). Matrix 3 in the organs' domain represents parametrical activities in the selection of the suitable active elements or organs and their mode of action for interdisciplinary artefacts that create suitable performance effects. Matrix 4 in the part design domain is focused on the allocation or distribution of the organs in the parts, which can be produced and assembled so that all system's performance tasks are solved and its totality behavior assured.

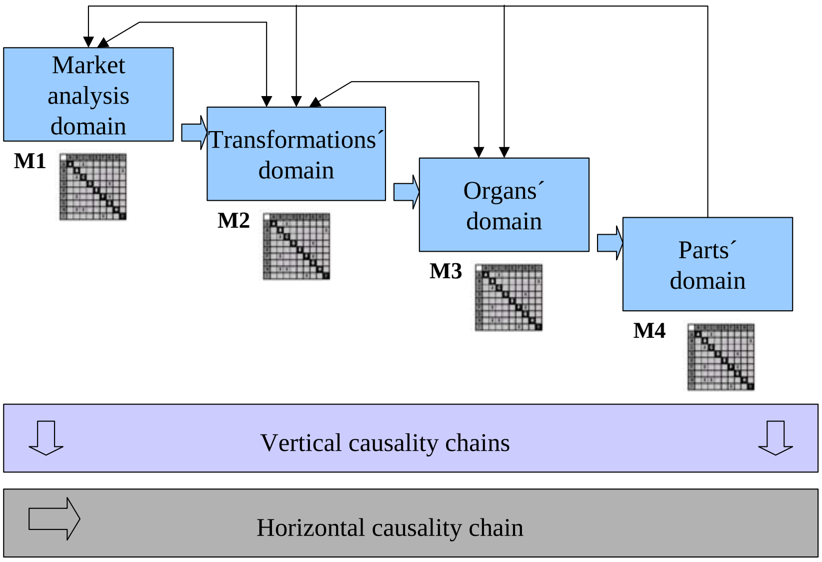


Figure 7. The integrated model for interdisciplinary system design

When positioning the described synergy-based approach in the engineering design methodologies environment, the main contribution will be the introduction of an additional synergy dimension for integration. The synergy dimension is introduced to 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 clear up the processes scheduling. Using the synergy-based approach to engineering design a new family of adaptive design tools can be developed, based on the level of competence and expert knowledge of the design team. Thus, a way for synthesizing a design team's own roadmap algorithm to move ahead the design process is opened. In this process, the statistical probability evaluation of the time for iterations, reworks and learning may be used (Cho, 2001). However, it is not easy to use the proposed tool. It is complicated and time-consuming to compose a useful and suitable DSM matrix, and this may be a great challenge to a design team. The problem is that the DSM is set up based on expert knowledge and competence of the design team. Thus, simultaneous professional knowledge of product architecture, product development process and organizational work is required and success in the design model use depends on the existence of these qualifications. The professional team is always supported by the automatic synthesis of the optimal design algorithm that leads to improved product performance during the shortest design time. The low competence of the design team results in imperfect DSM where some important interactions may be absent or incorrectly evaluated. The described circumstances cannot reduce the values of the present approach as any methodology may prove ineffective because of an incompetent team.

4.2 Selection of a mathematical approach for DSM processing

The mathematical theory of matrixes was founded between the 19th and the 20th century and has had a substantial progress during the last century. Thus, the present research has a benefit of choosing from a variety of tools suitable for attaining the goals of synergy-based design. Numerous publications in the field of DSM technology starting from Steward up to nowadays were analyzed (Pimmler & Eppinger, 1994; Malmqvist, 2001; Browning, 1998; Kusiak & Wang, 1993; Morelli et al., 1995; Gulati & Eppinger, 1996; Malmström, 1998; Baldwin & Clark, 1998). A good classification of DSM was given in (Browning, 1998) where the application areas of the matrixes clustering and sequencing technology are presented. On the basis of this approach, for the three first domains in Fig. 7 the sequential approach is more suitable and for the last one both sequential and clustering approaches can be used. Consequently, the mathematical tools have been initially determined to support the activities to improve the effectiveness and predictability of design processes and to guide project management efforts throughout the development process.

The proposed model should follow the synergy-based approach of the information management in the DSM method and the efforts to use the advanced simulation techniques, such as the Latin Hypercube Sampling (LHS) and parallel discrete event simulation (Cho, 2001). Thus, the analytical features are to be included so that the model is able to describe the complex behavior of the development processes having overlapped tasks and sequential iterations. The DSM method here is used to structure the information flows among tasks and capture the iteration loops. This allows for computing the probability distribution of lead-time in a resource-constrained project network where iterations take place among sequential, parallel and overlapped tasks. By establishing the information flow dependencies, a critical dependency path is identified and redundant constraints are removed for the modeling and scheduling analyses. In each simulation run, the expected durations of tasks are initially sampled using the LHS method (Keefer & Verdini, 1993; Browning, 1998, Cho, 2001). In addition to this, it is possible to distinguish two types of information flows in a task information flow at the beginning or at the end of the task, and an information flow in the middle of the task (Fig.8).

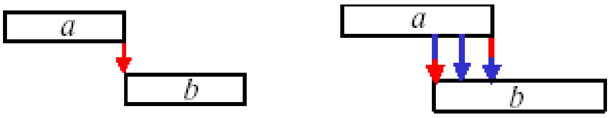


Figure 8. Types of information flows

Iteration is defined as rework caused by other tasks without including repetitive work within a single task. It is assumed that overlap amounts as well as expected rework impacts between the two tasks can be estimated in the planning stage.

A special feature of this model is the use of the triangular probability distribution to represent the characteristic of a task duration since it offers comprehensibility to a project planner (Williams, 1992). The probability density function for this distribution is a triangle with a distribution minimum at *a*, a distribution maximum at *c*, and a most likely value at *b* (the apex of the triangle). The values of the parameters must be such that $a < c$, and b must be located within the inclusive region [*a*, *c*] (Wyss & Jorgensen, 1998). In this context, it is suitable to use the Latin Hypercube Sampling (LHS) method to incorporate the uncertainty of the expected duration of a task based on three estimated durations (values *a*, *b*, *c*) – optimistic, most likely and pessimistic. It is necessary to underline that the expected duration is the duration between the start and the end of its continuous work, even though the task may iterate more than once afterwards.

In summary, it is necessary to underline the flexibility and suitability of the described approach for setting the synergy-based priorities. It makes it possible to realize the negative synergy filtration principles and to reach to the optimal synergy level, set by the market, during minimal time. The question raised concern the competence level required to use the proposed simulation method, although all of these mathematical tools are available in most of the mathematical software. A full exploitation of the possibilities of the proposed approach needs an experienced professional team and pays back at a complicated system. But an effective use of the proposed methodology is possible also with less professional teams and less complicated systems where the synthesis of the optimal decision-making algorithm for the design process is the first priority. No methodology can be so adequate as to suite any competence level of a design team.

4.3 Case study for the development of an accurate positioning system

The task of stepping up the synergy level of allied technologies has a goal to reach the market-driven performance with minimal possible expenses on product development and production. The practical realization of these guidelines is appropriate to be demonstrated on the basis of a real case study, which was initiated to improve the accuracy of the existing pneumatic positioning system (see Fig. 9).

The dependence of the initial positioning accuracy on the positioning speed was determined experimentally and the results are shown in Fig. 10. This positioning accuracy (repeatability) contains the dispersion of switching time of the controller and the pneumatic control valve and also the accuracy of the measuring device. It is obvious that the positioning system overrun from the moment of getting the positioning signal to the full stop can be compensated only by pre-scheduling of the initial signal.

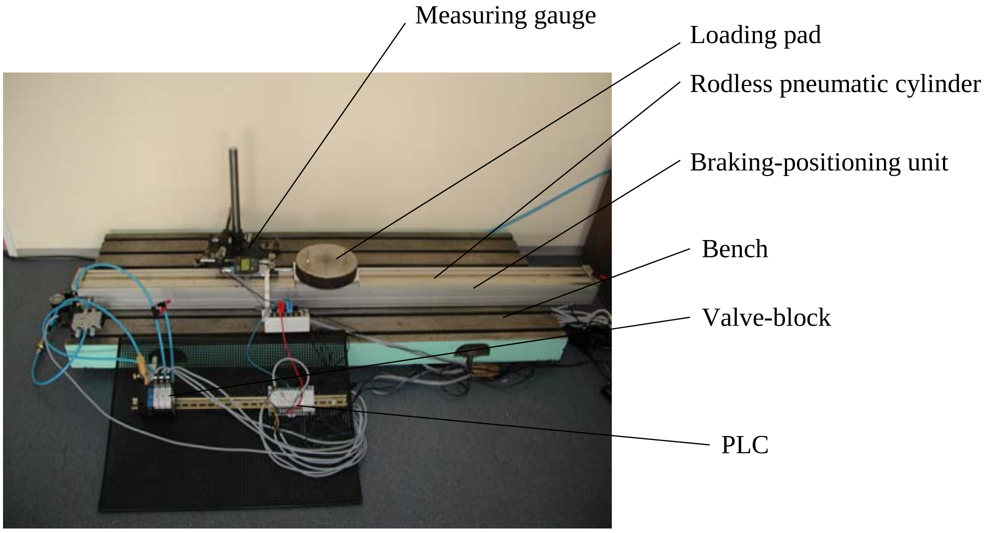


Figure 9. Experimental stand

From the point of view of the design activities, this case certainly belongs to the category of past design or modernization and therefore does not need the full content of the design activities as compared with the design of a functionally new product. Thus, in the framework of research it is suitable to draw up only two matrixes: the activity-based DSM for the market analysis domain and the parameter-based DSM for the integrated transformations' and organs' domain. As the composing of matrixes needs wider expert knowledge, the expert group was enlarged by a special survey among Estonian / Finnish users and producers of automated equipment.

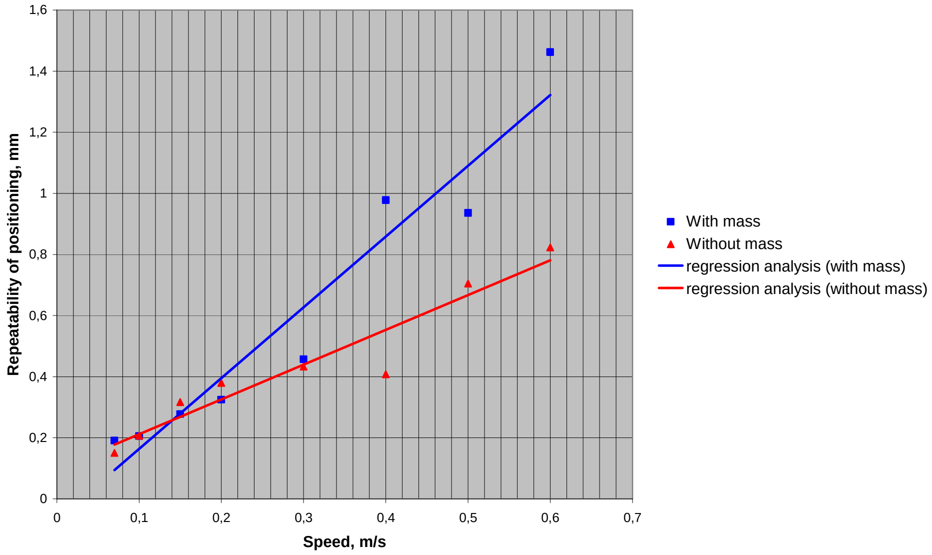
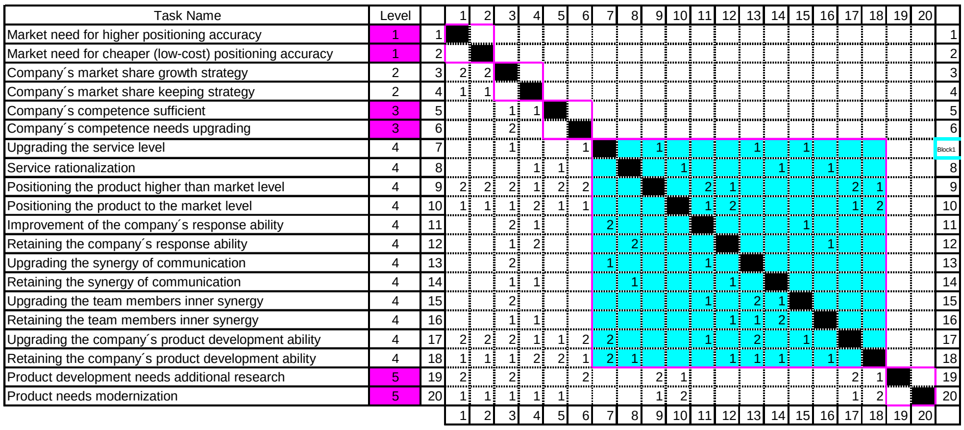


Figure 10. **Initial positioning repeatability of a pneumatic positioning system**

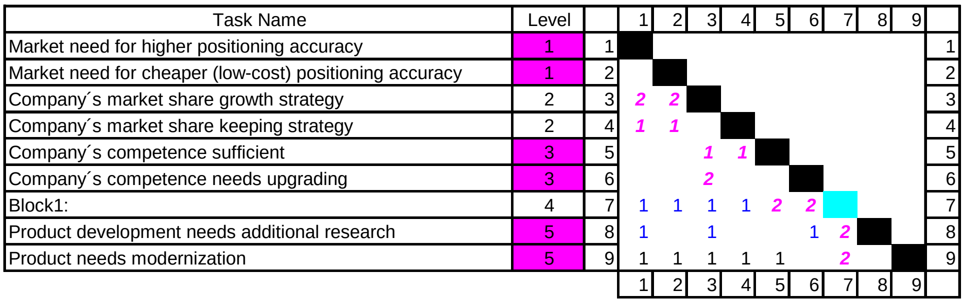
For the market analysis domain, the DSM for 20 inputs was compiled, characterizing trends in the present market environment, the product strategy of the company and its personnel competence in product development. It is necessary to point out that the DSM technology is not able to work at contradictory presumptions, for example, simultaneously for a growing and a decreasing market. The present automation market in the Nordic countries is supposed to be decreasing. All interactions in matrixes were evaluated from the synergy point of view. So far it is suitable to distinguish three categories of synergy integration: 0 – synergy is small or absent at all, 1 – synergy is moderate and 2 – synergy is very strong and decisive for a the product or system performance.



Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Market need for higher positioning accuracy	1	1	■																				1
Market need for cheaper (low-cost) positioning accuracy	1	2		■																			2
Company´s market share growth strategy	2	3	2	2	■																		3
Company´s market share keeping strategy	2	4	1	1		■																	4
Company´s competence sufficient	3	5			1	1	■																5
Company´s competence needs upgrading	3	6			2			■															6
Upgrading the service level	4	7			1			1	■		1				1		1						Block1
Service rationalization	4	8				1	1			■		1				1		1					8
Positioning the product higher than market level	4	9	2	2	2	1	2	2			■		2	1					2	1			9
Positioning the product to the market level	4	10	1	1	1	2	1	1				■	1	2					1	2			10
Improvement of the company´s response ability	4	11			2	1			2				■				1						11
Retaining the company´s response ability	4	12			1	2				2				■				1					12
Upgrading the synergy of communication	4	13			2				1				1		■								13
Retaining the synergy of communication	4	14			1	1				1				1		■							14
Upgrading the team members inner synergy	4	15			2								1		2	1	■						15
Retaining the team members inner synergy	4	16			1	1								1	1	2		■					16
Upgrading the company´s product development ability	4	17	2	2	2	1	1	2	2				1		2		1		■				17
Retaining the company´s product development ability	4	18	1	1	1	2	2	1	2	1				1	1	1		1		■			18
Product development needs additional research	5	19	2		2			2			2	1							2	1	■		19
Product needs modernization	5	20	1	1	1	1	1				1	2							1	2		■	20
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	

Figure 11. **Activity-based DSM for market analysis after partitioning**

Fig. 11 shows the activity-based matrix for market analysis, already allocated to partitioning transformation. In this transformation process, activities are ranged with a goal to move all the interactions under the diagonal that lead to the possibility to use the information of previously completed actions in the chain of activities. In the real situation, this ideal opportunity is usually impossible, as sometimes parallel actions are necessary and in some cases, the solution of a current task needs some feedback information from a later activity and those bounded tasks are grouped into an outlined block. Now we have reached the first goal – all activities are scheduled by the best possible way to make it possible to work out the company's survival policy for the period of decline in the industry. All the activities are also grouped on the levels, marking the decision-making steps. In the present case, as the first level, market analysis is necessary to be provided. The two next levels form an invisible block of SWOT analysis. On the fourth level, all the problems with product development capability and personnel upgrading problems should be solved. On the last level, decisions have to made about product modernization and research help from universities. This is a simple demonstration case and someone may say that it is a normal way of scheduling of activities possible without any DSM. However, commonly, research tasks are more complicated, moving out from the brain seizure. Here it is also necessary to pay attention to the fact that process scheduling is the only first step of the process and the still visible information about synergy of interactions is so far only partly used. After the collapse of the blocks in the matrix and the analysis we reach the activities timing problems (see Fig. 12).

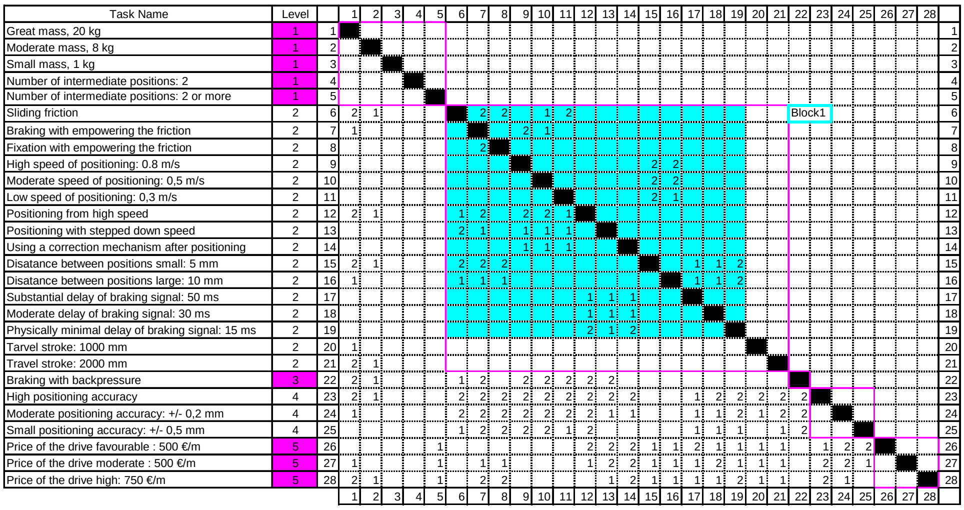


Task Name	Level		1	2	3	4	5	6	7	8	9	
Market need for higher positioning accuracy	1	1	■									1
Market need for cheaper (low-cost) positioning accuracy	1	2		■								2
Company´s market share growth strategy	2	3	*2*	*2*	■							3
Company´s market share keeping strategy	2	4	*1*	*1*		■						4
Company´s competence sufficient	3	5			*1*	*1*	■					5
Company´s competence needs upgrading	3	6			*2*			■				6
Block1:	4	7	1	1	1	1	*2*	*2*	■			7
Product development needs additional research	5	8	1		1			1	*2*	■		8
Product needs modernization	5	9	1	1	1	1	1		*2*		■	9
			1	2	3	4	5	6	7	8	9	

Figure 12. **Timing analysis of the process**

It is possible to distinguish the critical bindings (numbers in italics) in the iteration context of the information transfer, to prognosticate the probabilistic duration of the whole process, providing all the activities an optimistic, likely and pessimistic evaluation of duration, taking into account the learning time (see in more detail in Cho & Eppinger, 2001). But here it is necessary to remind the main goal of the present research - to reach the optimal synergy between all interactions in all the levels of problem-solving. At the same time, it is necessary to warn that in strongly intertwined inputs for a process difficult to schedule (market analysis is one of these) it is necessary to concentrate only on strong interactions, as a dissipating use of interactions may lead to the situation that partitioning becomes impossible. But in any case, the trustworthy roadmap for a development process is created with a possibility of keeping a comprehensive overview of the decision-making process.

To drawn up the parameter-based DSM for the allied domains of transactions and organs, initially 40 inputs were nominated from which 28 were selected for the final matrix after careful selection. The same procedure of the evaluation of synergy-based interactions on 2-1-0 scale was provided. In Fig. 13, the parameter-based DSM after partitioning is presented. The expected outcome from this analysis is a proposal for the structure of a more exact pneumatic positioning device at a moderate price increase. As one can see, the five levels of inputs are distinguished. On the first level, the invisible block of the initial parameters having no interactions is seen. The second block is a real design matrix where all the important design parameters supporting the performance of the product are presented. The last three levels are carrying the output parameters feature where the ultimate use of the backpressure in the cylinder during braking is estimated. The last two levels belong to positioning accuracy and price level - to problems that cannot be solved earlier.



Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	
Great mass, 20 kg	1	1	■																												1
Moderate mass, 8 kg	1	2		■																											2
Small mass, 1 kg	1	3			■																										3
Number of intermediate positions: 2	1	4				■																									4
Number of intermediate positions: 2 or more	1	5					■																								5
Sliding friction	2	6	2	1				■	2	2		1	2											Block1							6
Braking with empowering the friction	2	7	1						■		2	1																			7
Fixation with empowering the friction	2	8							2	■																					8
High speed of positioning: 0.8 m/s	2	9									■						2	2													9
Moderate speed of positioning: 0,5 m/s	2	10										■					2	2													10
Low speed of positioning: 0,3 m/s	2	11											■				2	1													11
Positioning from high speed	2	12	2	1				1	2		2	2	1	■																	12
Positioning with stepped down speed	2	13						2	1		1	1	1		■																13
Using a correction mechanism after positioning	2	14									1	1	1			■															14
Disatance between positions small: 5 mm	2	15	2	1				2	2	2							■		1	1	2										15
Disatance between positions large: 10 mm	2	16	1					1	1	1								■	1	1	2										16
Substantial delay of braking signal: 50 ms	2	17												1	1	1			■												17
Moderate delay of braking signal: 30 ms	2	18												1	1	1				■											18
Physically minimal delay of braking signal: 15 ms	2	19												2	1	2					■										19
Tarvel stroke: 1000 mm	2	20	1																			■									20
Travel stroke: 2000 mm	2	21	2	1																			■								21
Braking with backpressure	3	22	2	1				1	2		2	2	2	2	2									■							22
High positioning accuracy	4	23	2	1				2	2	2	2	2	2	2	2	2			1	2	2	2	2	2	■						23
Moderate positioning accuracy: +/- 0,2 mm	4	24	1					2	2	2	2	2	2	2	1	1			1	1	2	1	2	2		■					24
Small positioning accuracy: +/- 0,5 mm	4	25						1	2	2	2	2	1	2					1	1	1		1	2			■				25
Price of the drive favourable : 500 €/m	5	26					1							2	2	2	1	1	2	1	1	1	1		1	2	2	■			26
Price of the drive moderate : 500 €/m	5	27	1				1		1	1				1	2	2	1	1	1	2	1	1	1		2	2	1		■		27
Price of the drive high: 750 €/m	5	28	2	1			1		2	2					1	2	1	1	1	1	2	1	1		2	1				■	28
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	

Figure 13. Parameter-based DSM after partitioning

Let us concentrate on the central block where the key of the expected solution is concealed. The synergy level in braking with friction is stretched from the deep negative synergy at small velocities (perky movement) up to a maximum at the physically impossible instant braking with an enormous braking force. At the same time, friction is absolutely necessary at fixing the achieved position as this is much cheaper and more accurate, attained by the use of expensive servo systems.

The increasing friction in combination with the backpressure in cylinder in the present prototype seems to be a good idea but it does not give the expected accuracy of the result. The best solution of the problem is a situation where all the participating elements are integrated on the basis of maximum synergy of their mutual interaction. It means that the system must built on the basis of roller sideways and with the control servo at optimal speed having a separate braking system. However, all together it will be so expensive that it is impossible to sell those on the market. A constructive idea of the present research is to compress the system to the dimensions of the correction device without losing the synergy of action. It results in the correction mechanism with a cheaper shortest roller slide and friction-free elastic pneumatic drive controlled by the pressure, proportional to the positioning error. The model of this system was experimentally tested (see Fig. 14) and the results are shown in Fig. 15.

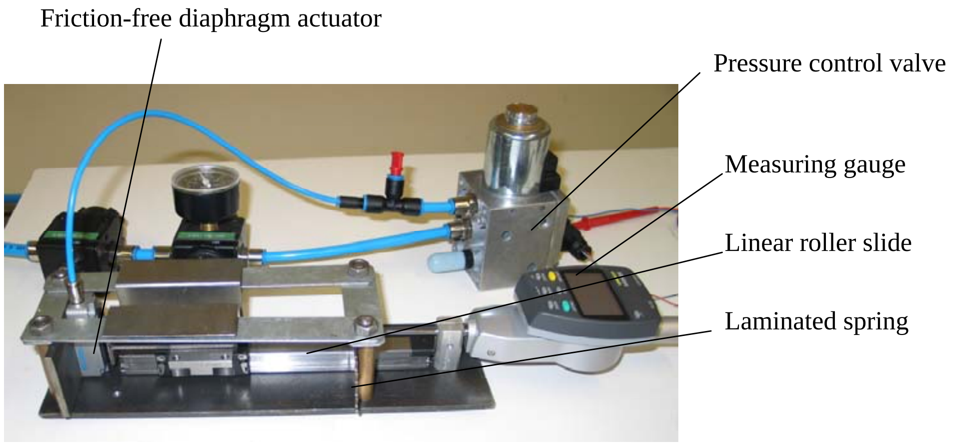


Figure 14. Testing the model of the correction device

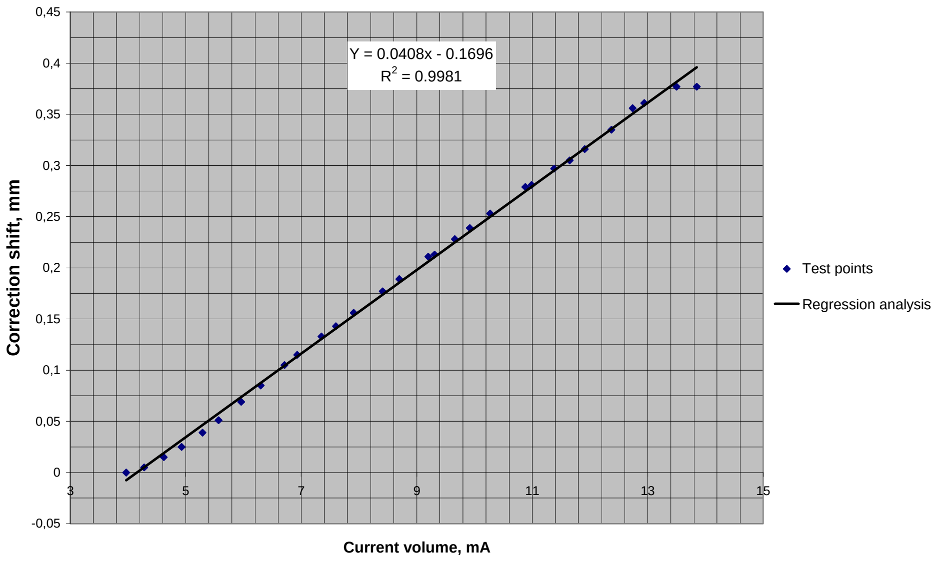


Figure 15. Final positioning accuracy of a pneumatic positioning system

One can see that the accuracy of the model much higher than the market expectations. The estimated price of the system is 40-50% higher than that of the prototype. It is explained by the physical-logical optimization to increase the synergy of the system. Thus, the situation is reached where cooperation capabilities of the system elements are used in a synergy-based manner on the optimal level, taking into account price limits on the market. That is the essence of a synergy-based design.

4.4 The modeling approach to system performance verification

Although enthusiasm in relation to outstanding capabilities of the synergy-based design by its innovative solutions offers different technologies integration capabilities and timing possibilities, another side of the problem - to filter out the casual mistakes or negative synergy in the logical behavior of the designed system should not be ignored. Applications of interdisciplinary systems have set high requirements to their reliability, fault tolerance and safety. Modern design approaches rely on the principle that safety and reliability constraints have to be followed during the whole development process and product lifetime. Problems of the validation of interdisciplinary designs are frequently involved with different speeds of electrical and mechanical processes, where large time constants make the exhaustive real-time tests very expensive. Testing techniques for validating large interdisciplinary systems are incomplete and cannot provide the required confidence. Examination of all the event combinations that may cause safety faults is often practically impossible.

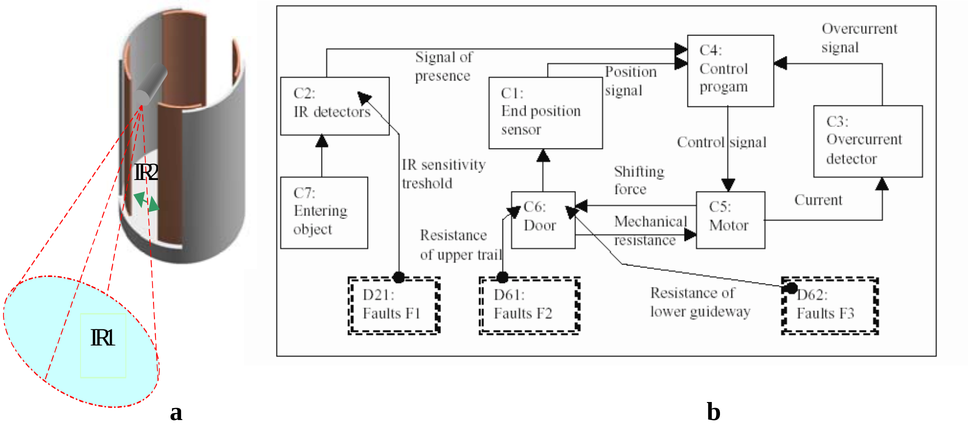
Validating the correctness of the design of interdisciplinary systems is becoming a significant part of the development cycle and also of the budget. The observations discussed above have led to the conclusion that traditional design validation methods, such as simulation and testing, although proved to be very useful, are insufficient for providing full confidence in design correctness and have to be combined with automated verification methods that perform an exhaustive state space exploration using advanced abstraction and approximation techniques. To prove safety properties in the presence of degradation effects of components of the system, more attention has been paid to formal verification methods and in recent years particularly to the Model Checking (MC) techniques. Using the Clock Difference Diagrams (CDD), a model-checking tool UppAal (Larsen et al., 1997) transforms the analysis space into the finite abstraction that can be decided efficiently and is appropriate for diagnostic trace generation.

To use this approach in the framework of the present doctoral research, cooperation with the research group of the Department of Computer Science of TUT headed by Prof. Jüri Vain, was established. This group is highly experienced and internationally active in the development of verification methods for large mechatronic systems. The question may crop up why two different case studies are used to verify the results of the findings of the present research. The reason to it is that in the last year to the initially planned case study of automated sliding doors (Vain et al., 2002) another case had to be added because of an urgent task to increase the accuracy of existing positioning systems.

The construction of design models and the application of the verification technique is explained on the basis of a sliding door example. As a case study the control example of a sliding door is described with three possible failure classes and the ways of its formalization are shown. A sliding door (see Fig. 16,a) is a simple but a representative example of a mechatronic class of an interdisciplinary system with relatively high safety requirements that can be violated by natural aging of components and different degradation phenomena. For simplicity, only the most common faults are analyzed here. The operation time between similar failures is measured by the expected service free operation time (ESFOT). This estimate is achieved by using a certain probability threshold. Service in our context may mean either replacing the whole functional unit or simple maintenance, e.g., cleaning. The sliding door consists of a pair of moving doors that open when an external wide range infrared sensor IR1 detects a moving object in the 2 m radius in front of doors, the door is kept open when internal infrared beam IR2 is interrupted and the doors are closing when during 2 sec there is no movement in IR1 sensitive area and beam of IR2 is present. The door has supply current and end position sensors. The door must be safe in the sense that if something happens with its mechanical or electronic components, no unpredicted opening or closing is allowed. Namely, basic design requirements are stated as follows:

Bounded reachability properties:
P1: If IR1 or IR2 sensors detect an object in its active area the door must be opened as a maximum in the time period T_{open}. $A\Diamond((IR\_sensor = ON \wedge Clock = 0) \Rightarrow (Clock \le T_{open} \Rightarrow (Door = OPEN))$, where "ON" and "OPEN" denote symbolic values of resp. IR sensor and door status variables.
P2: If there is no object in the door's active area during T_{wait} and doors are opened, then they must be closed in T_{close}. $A\Diamond((Clock \le T_{wait} \Rightarrow IR\_sensor = OFF) \Rightarrow (Clock \le T_{wait}+T_{close} \Rightarrow (Door = CLOSED))$, where "OFF" and "CLOSED" are symbolic values of resp. IR sensor and door status variables.

Safety properties:
P3: The door is never allowed to close whenever there is something in between the doors and after releasing the active area it must wait at least more T_{wait} time units. $A[](IR\_sensor = OFF \wedge Clock \le T_{wait}) \Rightarrow Door = CLOSED)$.
P4: The doors must stop in T_{react}, regardless of the direction of movement if a mechanical obstruction is present. $A[](Overcurrent = ON \Rightarrow Clock \le T_{react} \wedge Control = OFF)$, where Overcurrent is the output variable of the component C3 and Control the output of C4.



a **b**

Figure 16. Sliding door and its component model

Fault classes:

F1: Faults of infrared sensors IR1, IR2. Fault behaviour is skipping of existing objects or sensing of disturbances: the door does not open or is continuously open. The most common reasons for F1 class failure are: aging of infrared sensors that leads to increased threshold level; soiling of IR optics; strong background IR radiation. Those processes determine ESFOT as follows: electrical operating time of IR transceivers - 10 years; cleaning interval – 15 days. Arrival pattern of F1 fault class can be periodic or sporadic. F1 fault can be detected by measuring the open state time. After a certain time, out the algorithm should proceeds with slow speed closing.

F2: Fault class exhibits a increased mechanical rub in the upper rail. The common reason is wearing of the rail and bearings, resulting in low speed reaction. The power of the motor is insufficient to move the door with the required speed but no strict overcurrent condition is present. Averaged service free operating time between F2 type faults is expected to be about ten years. Arrival pattern of F2 is strictly periodic. The fault detection algorithm measures the time required for full range turn and/or measures the motor current.

F3: The fault that occurs when there is an obstruction in the lower guideway. Fault behavior is a sudden stop of the moving door, which can be detected by the overload condition of the current sensor. Arrival pattern of F3 fault is sporadic and not related to aging of components.

Based on the consideration described above it is possible to start the composition of the verification model. Since the door is symmetric in its behaviour we present the Control Component Pattern model only for one pair of doors and its control loop. Structurally, the model follows the same architecture that the system has. The main components and their inputs/outputs are shown in Fig. 16,b. Besides their basic functionality, the degrading components include D-subcomponents that model aging and are specified above fault classes F1-F3. To run the model checking procedure, the component model is transformed at first into the timed automata representation using a XML-based transformer (see Fig. 17). Correctness properties are formalized in the linear time temporal logic LTL, as described at bounded reliability and safety properties.

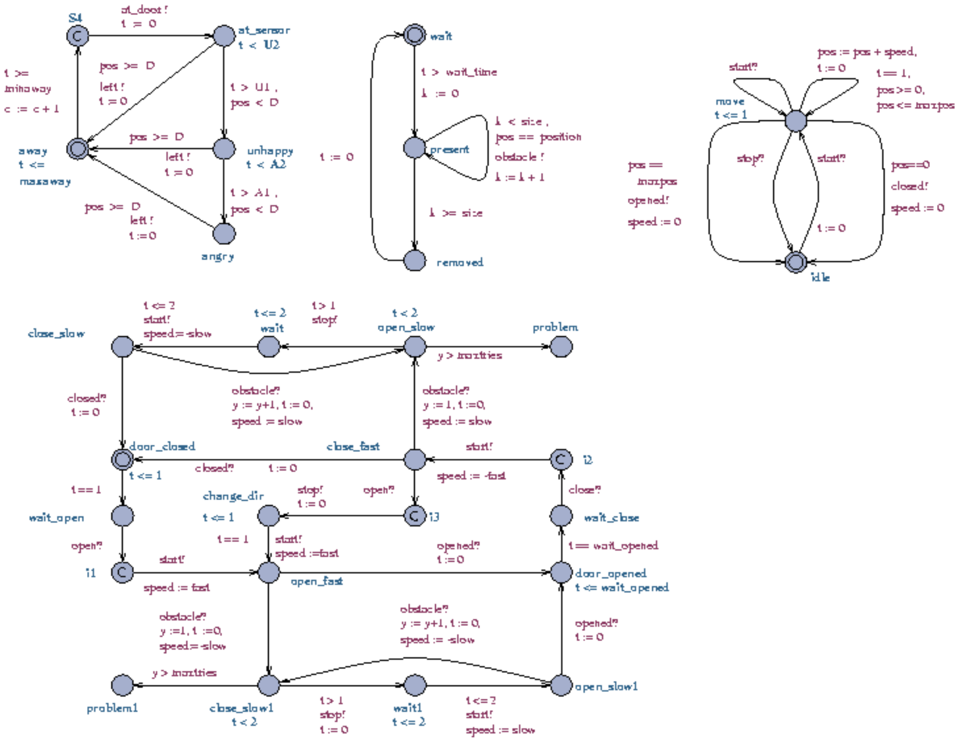


Figure 17. Sliding door represented as timed automata

The result of such analysis enfolds all the existing states of the door and offers therefore full confidence of correctness. MC has several advantages over other design validation methods. It conducts an exhaustive exploration of all possible behaviours, whereas simulation and testing are incomplete leaving unexplored behaviours in the model that may contain fatal bugs. MC is fully automatic and allows counter example (diagnostic trace) generation. It is also easy to integrate by help of testing and simulation tools. On the other hand, difficulties of MC are related to model construction, property specification and the complexity of model state space exploration. Practical tests with the given sliding door design have confirmed the faults initially predicted by our formal modeling and verification approach.

4.5 Conclusions to Chapter 4

1. A 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. To solve this task, a suitable background framework of engineering design methodologies has to be found, enabling one to involve synergy metrics and human competence dimensions into the design process. It was shown that the integration of the Design Structure Matrixes (DSM) technology and the Theory of Design Domains (TDD) is a suitable basis for this purpose and makes it possible to develop a new family of adaptive design tools.
2. The DSM technology is a suitable basis for information management of the synergy-based design of the interdisciplinary systems as it makes it possible to describe the interactions of their parameters and components, design team cooperation and market situation in the synergy-based manner to keep them visible during the whole design process.
3. As a basis for the decision-making structure at the design of interdisciplinary systems, the TDD is most suitable. This approach allows for the control of the advancement in the design process in the 3-dimensional design space: undetailed – detailed, abstract – concrete and in the step of the realisation of the artefact. Applying the three views of the products: transformations´, organs´ and parts´ domains, this theory is composed of substantial classes of structural definitions and behaviour of the artefacts designed.
4. The integration of the DSM technology and the TDD opens a door to adaptive design methodologies, making it possible on the basis of the expert knowledge of the design team to synthesize an optimal decision-making roadmap. The synergy dimension is introduced to the DSM in the form of the evaluation of its integration power in the parameters and processes on a 3-step scale.
5. To involve the time dimension into the processing of the DSM the best solution seems to be the use of the further development of Monte Carlo statistical modelling by LHS or Latin Hypercube Sampling that opens a possibility for probability-based simulation of the sequence of mutually dependent processes. Thus it is possible to plan the development of the complicated probability evaluation processes containing iterations, rework and learning, to avoid superfluous over- or underestimation at resource planning.
6. As a result the testing of the proposed framework for interdisciplinary systems synergy-based design for market analysis and integrated transformations´ domains this approach has proved suitable. Processing the structure matrixes composed on the basis of expert knowledge design allowed for a conclusion that the decision-making algorithm in terms of its structure is a good basis for synergy-based logical optimisation of the system designed. The proposed approach applied to redesign the pneumatic

positioning system has given increased accuracy at the competitive market price. The validity of the proposed design has been proved experimentally.

7. It was shown that to avoid casual logical mistakes at the complicated safety-critical interdisciplinary systems design, the virtual mathematical testing based on the timed automata model is appropriate. The case study of the use of this approach is presented in the last chapter of the present thesis.

CONCLUSIONS AND FURTHER RESEARCH

It is appropriate to discuss the findings of the present theses in three aspects: research results and their application, novel findings, and further development of the research. The aim of this research is to develop a possibly complete concept of the use of the synergy-based approach in the design of interdisciplinary products and systems to attain the maximum synergy of the allied technologies performance.

To attain this goal, four basic problems have been solved:

- a thorough analysis of the existing engineering design methodologies to form a suitable basis for the development of synergy-based methodologies for interdisciplinary systems design is presented;
- a complete concept of the synergy-based treatment of the interdisciplinary systems design parameters in the positive and negative synergy context is proposed;
- experimental research focused on the synergy-based aspects of engineering activities, based on the comprehensive analysis of the equipment control and factory automation systems design and a database of application shortcomings is described;
- the strategy and methododical framework for the synergy-based design of interdisciplinary systems is developed and verification of its applicability is provided.

During this doctoral research the following conclusions have been reached:

1. First, it is necessary to position the present doctoral research in the environment of existing engineering design methodologies. Around the beginning of the present century the international engineering design research community reached a somewhat confusing conviction that engineering design is not a pure technical problem any more but a complex activity, involving artifacts, people, tools, processes, organizations and conditions of the real economic environment. The arguments are especially true for interdisciplinary systems (mechatronic products, lighting devices etc.) where the complicated synergy aspects between allied technologies are added. Interdisciplinarity is used here as a short term to mark the integration of different allied technologies. In the launched race between research groups to fill this gap, our contribution - a new paradigm – the synergy-based approach to design is proposed. During the last years of the present century the attitude of the international research community to the proposed approach has changed from provisionally diffident to the positive recognition.

2. The increase of the integration of different technologies in new products with better performance and marketing power due to the best features of allied technologies has been an evergrowing tendency during the last decades. Thorough analysis of the existing engineering design methodologies has proved that all allied technologies have their specific design tools built up on different basis and this

situation does not show a trend for closer integration. Consequently, at the design of interdisciplinary products and systems it is reasonable to set one’s hopes on a more general or meta-approach and the synergy-based approach seems to be a good chance to solve this problem. Synergy here is treated as an effect between suitable integration when the whole is more than the sum of its parts.

3. To find the initial basis for the development of the synergy-based design methodologies a thorough analysis of today’s engineering design methodologies was conducted. A conclusion has been reached that the systems theory approach suits as a basis of the synergy-based methodology for interdisciplinary systems design and can be used as decision-making algorithm of the stage structure of the Theory of Design Domains (TDD). This is a capable tool for the synthesise of the complicated systems in a technology-independent manner, when moving in the decision-making process in the abstract – concrete and undetailed – detailed direction in every step of synergy-based integration. For the allied technologies information management the suitable basis is the Design Structure Matrixes (DSM) technology, allowing for the description of synergy-based interactions between systems components and design processes. The transformation of the matrixes makes it possible to involve scheduling and time dimensions into the design processes.

4. As a result of a previous doctoral thesis (Tähemaa, 2002) it was proved that the positive and negative synergy are objective realities at the design and exploitation of the mechatronic office equipment. In the present research this approach was enlarged to larger interdisciplinary systems used at equipment-control and factory automation. It was shown that from the point of view of the development of the design methodologies for interdisciplinary systems, the synergy is reallya universal indicator. By help of synergy it is possible to express all substantial parameters used in the design process, including quality, reliability, human factors, and competitiveness. As raising the synergy level needs remarkable resources, the optimal synergy level is determined by the market situation.

5. In the present doctoral research, a more detailed cognitative level has been reached, concerning the ways of increasing the positive synergy and suppressing the negative synergy effects. It is proved that for the quantitative evaluation of the synergy the per cent metrics is most favorable, where the 0-point situation denotes the “synergy-free” artefact. The maximum value on the positive side of this scale means reaching closer to the maximum synergy, or 100%, where everything has been squeezed out of physical processes. It was shown that the positive synergy at the integration of allied technologies into interdisciplinary systems is attainable by a rational integration of the physical, logical and mathematical optimization. In any case, it is not possible to ignore negative synergy facts on the negative direction of the scale due to their insidious action and a tendency to occur again. It was shown that the negative synergy is closely related to the reliability characteristics of the systems and it reveals itself mostly in the infant mortality period of a new product’s

life cycle. The classical understanding of a system’s reliability is not very suitable for interdisciplinary systems as besides mono-technology failures there are also combined failures or effects of incompatibility of the allied technologies interfaces (up to 24% of all failures). In the synergy context reliability it can be treated as a process where the synergy of operation of components is gradually reduced (wear, emission, etc.) and it stops functioning when the accumulating negative synergy reaches its extreme (-100%).

6. One of the main research targets of the present doctoral research is to clarify the synergy-based aspects of engineering activities. It is obvious that the success of the synergy-based approach to design depends on the competence and expert knowledge of the design team. Without a thorough and detailed research into the human impact on the so-called “bad” engineering it is impossible to evaluate the negative synergy in the teamwork and to differentiate the human and technical side in the negative synergy effects. During the last four years, a unique database of human and technical shortcomings was compiled, comprising more than 13000 equipment and five factory automation control systems and commissioning cases.

7. In the composed database of human and technical shortcomings in the equipment control and factory automation, all shortcomings occurring in the design and launch of the interdisciplinary systems were classified into three main categories: human faults, human mistakes and technical problems. All communication misunderstandings and any type of negligence belong to the faults category. The mistakes category involves wrong decisions caused by lack of competence and conditionally the mistakes caused by unknown matters at the moment of system design. It was shown that role of human factors at the formation of the negative synergy effects may be treated in the synergy-based manner – as lack of synergy in the teamwork or in person’s inner communication.

8. A successful separation of human and technical aspects in the design of interdisciplinary systems opens up new possibilities to move ahead on the way of their synergy-based design. To solve this task, a suitable background framework of engineering design methodologies has to be found, enabling one to involve synergy metrics and human competence dimensions into the design process. It was shown that the integration of the DSM technology and the TDD (see also conclusions 3 and 4) are a promising solution for this purpose. The DSM technology is a suitable basis for the synergy-based design of the interdisciplinary systems as it makes it possible to describe the interactions of their parameters and components, design team cooperation and market situation in the synergy-based manner and to keep them visible during the whole design process. The TDD is the most suitable basis for the decision-making structure in the design of interdisciplinary systems. Applying three views of the realization of the product: transformations´, organs´ and parts´ domains, this theory is composed of substantial classes of structural definitions and behaviours of the artefacts designed.

9. In the proposed framework of the interdisciplinary systems synergy-based design, the following DSM matrixes must be composed and analyzed. Firstly, the activity-type market analysis matrix should be constructed that takes into account the marketing trends and initiates the synergy-based activities in the firm’s product strategy planning to develop products competitive on the market. Secondly, the parameter-based DSM in transformations´ domain gives an algorithm for the design process and makes it possible to reach to the optimal synergy level and performance of the product designed. Thirdly, the DSM organs´ domain represents parametrical activities in the selection of the suitable organs and their mode of action for interdisciplinary artefacts. Finally, the DSM in the part design domain that is focused on the allocation or distribution of the organs in the parts, which can be produced and assembled so that all the system’s performance tasks are solved. The synergy dimension is introduced to the DSM in the form of evaluation of its integration power in parameters and the process on a 3-step scale. The procedure of processing the DSM matrixes makes it possible to chart scheduling and leveling of the decision-making process. It was shown that by using a synergy-based approach to engineering design it is possible to develop a new family of adaptive tools based on the level of competence and expert knowledge of the design team and to synthesize their own roadmap algorithm to move ahead in the design process.

10. The proposed framework of synergy-based design of interdisciplinary systems makes it possible to introduce probabilistic timing into the design process. To involve the time dimension into the processing of the DSM, the best solution seems to be the use of the further development of Monte Carlo statistical modelling by the LHS or Latin Hypercube Sampling that opens a possibility for the probability-based simulation of the sequence of mutually dependent processes. Thus, it is possible to plan the development of the complicated probability evaluation processes, containing iterations, rework and learning, to avoid superfluous over- or underestimation at resource planning.

11. To give the proof to the propagated approach of the synergy-based integration of allied technologies, a case study for raising the accuracy of the existing pneumatic systems was described. The dependence of initial positioning accuracy on the positioning speed was determined experimentally and at the speed interval 0.1 – 0.4 m/s it corresponded to +/-0.1 - +/-0.5 mm. The two matrixes – the activity-based DSM for the market analysis domain and the parameter-based DSM for the integrated transformations´ and organs´ domain were compiled. The constructive idea clarifying the result of the use the present approach is to compress the systems´ synergy-engenders to the dimensions of a correction device without losing the synergy of action of the whole system. The model of this system was experimentally tested and the accuracy expanded uncertainty of the model +/-0,00664 mm is far more accurate than market expectations. The estimated price of the system is 40 - 50% higher than that of the prototype.

12. To avoid casual logical mistakes at the complicated safety-critical interdisciplinary systems design, the virtual mathematical testing based on the timed automata model is appropriate to use. The case study of the use of this approach is presented in the last chapter of the present thesis.

The novelty of the present research lies in the following:

1. While evaluating the novel findings of the present research, the most important result is the arrival at the truth that the synergy-based approach to the interdisciplinary systems design is a real way to create a complete picture of all realities of the design process. It is obvious that the integration of different technologies into interdisciplinary systems cannot be treated as their simple summing but as a way of compensating their mutual weaknesses and amplifying the synergy of their integration. In the present research, for the first time, a complete treatment of synergy characteristics at the integration of allied technologies into interdisciplinary systems is presented. As a result, a new approach to the synthesis of interdisciplinary artefacts using the categories of positive and negative synergy of allied technologies is proposed.

2. The success of the proposed synergy-based approach at the interdisciplinary system design depends also on human factors – on the competence and expert knowledge of the design team. The present thesis presents unique data about start-up shortcomings of two categories of interdisciplinary artefacts: equipment control and factory automation systems. A special analysis was conducted to separate technical and human shortcomings in the equipment control and factory automation systems design and commissioning. For the first time, it was shown that most of human and technical shortcomings can be treated as synergy-based. As a result, a synergy-based approach to human faults and mistakes in the product development process was developed.

3. It was shown that the integration of the DSM technology TDD is a suitable basis for synergy-based design methodologies of the interdisciplinary systems. The optimal synergy level in this case is determined by market conditions. A new family of product development tools for the design of interdisciplinary products and systems was developed where the synthesis of the decision-making algorithm is based on the competence and expert knowledge of the design teams. A successful case study of synergy-based integration of allied technologies is described. In conclusion, the synergy-based approach to the interdisciplinary systems design seems to ensure that all the technical and human realities in the design process be taken into account.

Finally all the research goals of the thesis set in the introduction have been successfully completed. The novelty of the results of the present doctoral research have been continuously tested on the international and Scandinavian scientific forums. The acceptance of the majority of conference papers for oral presentation in the conditions of strong competition has enhanced confidence and given evidence that the results of this research are original and are of wide interest. The range of questions at conference presentations has been focused on above listed novelties area.

To evaluate the impact of this research on the future research it is necessary to point out two main tasks. First, it is necessary to apply the proposed synergy-based approach in the full-scale factory where all the proposed development processes - marketing, design, manufacturing and financing are fully integrated and products manufactured are outstandingly interdisciplinary. Cooperation in the movement in this direction has already started. It concerns the production of lighting devices, where a suitable complex of allied technologies: light formatting, aero- and thermodynamics, heat transfer, electronics and sheet metal technology are integrated. Secondly, another study is on the way where synergy-based approach is necessary to introduce in the quality assurance field where so far distancing efforts in engineering design for quality and factory level quality management systems need better integrating basis.

KOKKUVÕTE

Doktoritöö peamiseks eesmärgiks oli luua võimalikult terviklik süsteem sünergiapõhise lähenemisviisi kasutamiseks interdistsiplinaarsete toodete ja süsteemide projekteerimisel, saavutamaks liittehnoloogiate ja inseneritegevuse maksimaalne sünergia.

Et sellele eesmärgile jõuda, tuli doktoritöös tööülesannetena lahendada 4 olulist probleemi:

- korraldada seniste projekteerimisstrateegiate süvaanalüüs, eristamaks neist sobivad sünergiapõhise lähenemisviisi rakendamiseks;
- luua terviklik arusaam interdistsiplinaarsete süsteemide projekteerimis- ja toimimisparameetrite sünergiapõhisest käsitlusest positiivse ja negatiivse sünergia kontekstis;
- korraldada eksperimentaalne uuring inseneritegevuse sünergiapõhiste aspektide olemuse selgitamiseks, mis põhineks seadmeautomaatika ja automatiseeritud tehaste käivitusraskuste analüüsil;
- arendada välja strateegia ja luua raammetoodika interdistsiplinaarsete süsteemide sünergiapõhiseks projekteerimiseks ja kontrollida selle rakendatavust.

Kogu töö väitekirja raames toimus valdavalt loetletud punktide järjekorras ja algas olemasolevate projekteerimismetoodikate põhjalikust analüüsist. Selle analüüsi eesmärgiks oli leida sobilik baas, millele toetudes saaks jõuda kahele põhieesmärgile. Esiteks oli vaja leida sobiv otsustuste tegemise strateegia, mille raames saaks selgepiiriliste etappidena liikuda üldisemalt konkreetsemale, lahendades igas etapis projekteerimisülesandeid sünergiapõhiselt. Sünergiat käsitletakse siin efektina, kus tervik on suurem kui üksikute osade summa. Teiseks oli vaja leida võimalus toote või süsteemi komponentide siduste sünergiapõhiseks hindamiseks selliselt, et see info ei hajuks projekteerimise protsessi vältel. Analüüsides olemasolevaid tootearenduse ja projekteerimise metoodikaid ning hindamaks neis peituvaid võimalusi selgus, et interdistsiplinaarsete süsteemide projekteerimise metoodika kavandamisel oleks soodne lähtuda nii süsteemitehnika põhimõtetel põhinevast valdkondade teooriast kui ka konstruktsioonimaatriksite tehnoloogiast. Konstruktsioonimaatriksite tehnoloogia juures avaneb võimalus kõigi süsteemi komponentide ja elementide sünergiapõhiste seoste ülevaatlikuks ja põhjalikuks kirjeldamiseks. Konstruktsioonimaatriksite töötlemine võimaldab ajaliselt sünteesida otsustusprotsesside ahela, koondades tähelepanu just neile sünergiapõhistele sidustele, mida on vaja antud etapil arvesse võtta. Samas jääb kogu sünergiaalane info kättesaadavaks kogu projekteerimisprotsessi vältel. Üha enam muutub selgemaks, et ettekirjutavad projekteerimismetoodikad ei sobi innovaatiliste ülesannete lahendamiseks, pigem on vaja sünteesida meeskonna professionaalsusest sõltuvaid paindlikke otsustusalgoritme, mis viiksid sihile kiiremini ja väiksemate kulutustega. Seega tuleks ka projekteerimise metoodikat käsitada hoopis laiemas tähenduses - kui sünergiapõhiste tegevuste kogumit püstitatud eesmärgi saavutamiseks.

Teiseks suureks ülesandeks oli interdistsiplinaarsete süsteemide sünergiapõhise käsitluse süvendamine ja lõpuleviimine. Interdistsiplinaarsete süsteemide all mõistetakse siin eri tehnoloogiate liitmist süsteemi parema toimimiskvaliteedi saavutamiseks. Seejuures tuli lähtuda reaalsusest, et kõigi toodete, sealhulgas ka interdistsiplinaarsete projekteerimine sõltub üha rohkem toote tarbijakesksuse saavutamise vajadusest ja konkurentsisituatsioonist turul. Pidevalt kasvav konkurents ja toodete üha kiirenev uuendamine nõuavad radikaalset tootearendusaja lühendamist, kuid samas ka toodete kvaliteedi tõusu. Jõuti järeldusele, et interdistsiplinaarsete süsteemide projekteerimisel leidub reaalne väljapääs olukorrast, kui lähtuda uudsest sünergiapõhisest lähenemisest, mis põhineb liittehnoloogiate vastastikuste nõrkuste kompenseerimisel ja tugevate külgede võimendamisel. Töö käigus on tõestatud, et positiivne ja negatiivne sünergia on interdistsiplinaarsete toodete ja süsteemide toimekvaliteedi hindamisel sobivaiks näitajaiks, kusjuures nende kvantitatiivseks hindamiseks sobib kõige paremini protsentuaalne meetrika. Positiivse sünergia saavutamine põhineb füüsikalise, loogilise ja matemaatilise optimeerimise oskuslikul integreerimisel. Negatiivse sünergia peamisteks allikateks on aga liittehnoloogiate sobimatus ja projekteerijate vead ning ebapiisav kompetentsus. On veenvalt tõestatud, et projekteerimismetoodikate kavandamise seisukohalt on sünergia universaalne näitaja, milles on võimalik väljendada kõiki olulisi projekteerimisprotsessis kasutatavaid parameetreid, kaasa arvatud kvaliteet, töökindlus, inimfaktori mõju ja konkurentsivõime. Kuna aga sünergia taseme tõstmine on seotud märkimisväärsete kulutustega, siis määrab optimaalse sünergia taseme paraku turusituatsioon.

Kolmandaks sõlmküsimuseks antud töös oli inimfaktori mõju uurimine tehiste projekteerimise ja evitamise protsessile. Ei ole kahtlust, et toote kvaliteet sõltub meeskonna kompetentsusest ja tööstiilist, kuid selle hindamiseks ja mõjutamiseks puudusid seni selged kriteeriumid. Sellest tulenevalt koostati ulatuslik seadmeautomaatika ja automatiseeritud tehaste käivitusraskuste andmebaas, kus süstematiseeriti ligi 13000 juhtsüsteemi projekteerimise ja 6 automatiseeritud tehase käivitamisel esilekerkinud inimpõhised ja tehnilised takistused. Unikaalse andmebaasi koostamine ja analüüs võimaldas meile teadaolevalt esmakordselt eristada inseneritegevuse ja tehniliste probleemide osa süsteemide sissetöötamise perioodil selguvais negatiivse sünergia ilminguis. Selle andmebaasi statistilisel analüüsil õnnestus välja selgitada vigade põhjuslikkus meeskonnatöö kommunikatsioonis ja indiviidi otsustes. Samuti said eristatud ka meeskonna ebakompetentsusest ja tehnoloogia vaegarengust põhjustatud eksimused. Analüüsi tulemuste põhjal saab väita, et inimfaktori mõju saab käsitada sünergiapõhiselt – meeskonnatöö sünergiana ja indiviidi sisemise kommunikatsiooni sünergiana. Uurimistöö tulemusena on kavandatud meetmed süsteemide projekteerimis- ja evitamisprotsessis tekkida võivate inimpõhiste negatiivse sünergia ilmingute vähendamiseks ja positiivse sünergia tekke soodustamiseks. Koostatud andmebaasi analüüs tekitas idee paindliku projekteerimismetoodika loomiseks, kus otstarbekas tee tulemuseni jõudmiseks sünteesitakse vastavalt projekteerimismeeskonna kompetentsusele. See põhineks ekspertteadmiste baasil koostatud projekteerimismetoodikal ja edasistel ümbertegemiste ja õpiaegade tõenäosuslikul prognoosil. Sel moel oleks võimalik prognoosida ka tootearenduse aega ja selle efektiivsust.

Doktoritöö neljandas ja kokkuvõtvas osas on välja töötatud interdistsiplinaarsete süsteemide sünergiapõhise projekteerimise üldistatud raammetoodika, mis põhineb konstruktsioonimaatriksite tehnoloogia ja valdkondade teooria integreerimisel. Konstruktsioonimaatriksite tehnoloogia ja valdkondade teooria integreerimine võimaldab vastavalt projekteerimiseesmärkidele valida vajaliku integratsiooni vahendid ja metodoloogia, kasutades selleks konstruktsioonimaatriksite tehnoloogias kasutatavaid järjestamis- ja rühmitamisalgoritme ning valdkondade teooria horisontaalse- ja vertikaalse põhjuslikkuse seadusi. See avab võimaluse projekteerimisprotsessis identifitseerida ülesandeid sünergiapõhiste seoste baasil, koostada neist sünergiapõhiseid ülesannete gruppe ja optimeerida nende järjekorda ning reaalselt hinnata selleks kuluvat aega. Selle hübriidse mudeli eelisteks on paindlikkus ja võimalus arvesse võtta projekteerimise nn. “pehmeid” parameetreid, mis on seotud ühiskonna nõuete (turg, kvaliteet, ostueelistuste kujunemine, massiline tarbijakesksus jt) ja ka inseneritegevuse sünergiat (projekteerimise käigus tehtud vead ja võimalikud eksimused, inseneride kompetentsi tase, õpivajadused jt). Uurimistöö tulemusena tõdeti, et projekteerimismeeskondade tegevuste algoritm ei saa olla absoluutne, optimaalne igale meeskonnale, sest metoodikad ei saa olla ühtviisi sobivad algajatest koosnevaile ja professionaalseile meeskondadele. Otstarbekam oleks kui igal projekteerimismeeskonnal oleks sünteesitav temale omane ja optimaalse kompetentsipõhise tulemuseni viiv tegevuste algoritm ehk projekteerimismetoodika.

Iga doktoritöö oluliseks osaks on selle tulemuste õigsuse või rakendatavuse tõestamine. Sobivaks näiteks väljatöötatud interdistsiplinaarsete süsteemide sünergiapõhise projekteerimise raammetoodika kehtivuse testimisel osutus piduriga pneumaatilise positsioneerimissüsteemi täpsuse tõstmine. Kõigepealt sai eksperimentaalselt määratud olemasoleva positsioneerimisseadme algtäpsus. Edasi sai koostatud ja analüüsitud turuseoste ja ühendatud transformatsiooni ning organite valdkondade maatrikseid, sünteesides vajaliku otsustussüsteemi. Pakutud uudne lähenemisviis osutus otstarbekaks, avades tee suurema positsioneerimistäpsuse saavutamiseks konkurentsivõimelise hinna juures. Sel moel täiustatud süsteemi efektiivsuse tõestamiseks sai ehitatud positsioneerimissüsteemi mudel ja eksperimentaalselt näidatud, et senist positsioneerimistäpsust on võimalik kardinaalselt tõsta. Teise näitena on toodud aegautomaatidel põhinev süsteemi virtuaalne matemaatiline testimine, mida on otstarbekas rakendada loogiliste vigade vältimiseks keeruliste süsteemide sünteesil.

Hinnates käesoleva doktoritöö tulemuste uudsust tuleks siin välja tuua kolm momenti. Esiteks on välja pakutud uus sünergiapõhine lähenemisviis interdistsiplinaarsete süsteemide projekteerimiseks, mis võimaldab arvesse võtta nii tehnilisi, inimfaktorist tingitud kui ka turunõuetest johtuvaid reaalsusi. Seda pole seni suutnud klassikalised projekteerimismetoodikad. Teiseks on õnnestunud teadaolevalt esmakordselt luua tehiste projekteerimisel ja evitamisel tekkivate inimlike vigade ja eksimuste sünergiapõhine käsitlus. Kolmandaks on töös välja töötatud üldistatud raammetoodika interdistsiplinaarsete tehiste projekteerimiseks, mis võimaldab saavutada optimaalse sünergiataseme projekteeritavas tootes, tagades sellega edu konkurentsitingimustes. Selle projekteerimismetoodika uudseks momendiks on, et otsustusalgoritm sünteesitakse lähtuvalt projekteerimismeeskonna ekspertteadmistest ja see põhineb liittehnoloogiate sünergiapõhisel käsitlusel.

Väitekirja kokkuvõttes on antud ka suunised uurimistöö jätkamiseks, kus on viidatud vajadusele testida metoodikat reaalse ettevõtte tingimustes kogu integreeritud tootearendusprotsessi ulatuses ja uurida kvaliteedisüsteemide ja kvaliteedipõhise projekteerimise integreerimise võimalusi.

REFERENCES

Aarino, P. 1999. Use of Simulation in Mechatronic Machine Design. Post Graduate Seminar. Helsinki Technical University, pp. 1-25.

Andreasen, M. 1993. The Theory of Domains, Internal Note, Department of Control and Engineering. Technical University of Denmark.

Andreasen, M. M. 1980. Systememetoder paa system grundlag, Diss. Lunds Tekniska Hogskola, Sweden, (in Danish).

Baldwin, C. and Clark, K. 1998. Design Rules: The Power of Modularity, Boston, MA: Harvard Business School Press.

Ballard, G. 2001. Positive vs Negative Iteration in Design. Lean Construction Intitute. Oakland.

Birkhofer, H., Lindemann, U., Albers, A. and Meier, M. 2001. Product Development as a Structured and Interactive Network of Knowledge – a Revolutionary approach, Proceedings ICED 2001, Glasgow.

Blessing, L. 2003. What Is This Thing Called Design Research, In: Proceedings of the 14th International Conference on Engineering Design ICED 2003, Innovation in Products, Processes and Organisations, Design Society, Linköping, Sweden, pp. 9-10.

Boehm, B. and Bose, P. 1994. A Collaborative Spriral Software Process Model Based on Theory W, IEEE Software, USA.

Browning, T. 1998. Modeling and Analyzing Cost, Schedule, and Performance in Complex System Product Development. PhD thesis. Massachusetts Institute of Technology. Cambridgr, MA.

Bröhl, A.-P. 1995. Das V-Modell – der Standard für die Softwareentwicklung, 2. Auflage, Oldenbourg, München.

Buur, J. 1990. A Theoretical Approach to Mechatronic Design, Institute of Engineering Design, Technical University of Denmark.

Calderon. 2000. A Composable Simulation Environment to Support the Design of Mechatronic Systems. PhD Thesis. Carnegie Mellon University. Pennsylvania.

Cho, S. 2001. An Integrated Method for Managing Complex Engineering Projects Using the Design Structure Matrix and Advanced Simulation. MSc. Thesis. Massachusetts Institute of Technology. Cambridge, MA., USA.

Cho, S. And Eppinger, S. 2001. Product Development Process Modeling Using Advanced Simulation. Proceedings of DETC 01, ASME 2001 Design Engineering Technical Conferences and Copmputers and Information in Engineering Conferences. Pennsylvania, USA.

Clarkson, P. J., Simons, C. and Eckert, C. 2001. Predicting Change Propagation in Complex Design. Proceedings ASME DETC-2001, Paper No DETC2001/DTM-21698.

Cooper, R. 2001. Winning at New Products, 3rd ed. Cambridge: Perseus Publishing.

Eppinger, S., The Design Structure Matrix- DSM, http://www.dsmweb.org, 12.11.2004.

Eppinger, S. D. and Salminen, V. 2001. Patterns of Product Development Interactions. Proceedings of ICED 2001, Glasgow, Scotland.

Eppinger, S., Whitney, D., Smith, R., and Gebala, D. 1994. A Model-Based Method for Organizing Tasks in Product Development, Research in Engineering Design, vol. 6, no. 1, pp. 1-13.

Erixon, G. 1998. Modular Function Deployment - A Method for Product Modularisation. PhD thesis, Royal Institute of Technology, Stockholm, Sweden.

Fagerström, J., Aganovic, D., Nielsen, J. and Falkman P. 2002. Multi-Viewpoint of the Innovation Systems – Using a Hermeneutic Method, Proseedings of ICAD2002, Second International Conference on Axiomatic Design, Cambridge, USA.

Gilb, T. 1988. Principles of Software Engineering Management, Addision-Wesley Publishing Company.

Grausemeier, J. and Moehringer, S. 2003. New Guideline VDI 2206 - a Flexible Procedure for the Design of Mechatronic Systems. ICED 03. Stockholm.

Gulati, R. and Eppinger, S. 1996. The Coupling of Product Architecture and Organizational Structure Decisions. M.I.T. International Center for Research on the Management of Technology, Working Paper no.151.

Hallin, K., Zimmerman T., Svensson D. and Malqvist J. 2003. Modelling Information for Mechatronic Products, ICED 03. Stockholm.

Hansen C.T. and Andreasen M.M. 2003. A Proposal for Enhanced Design Concept Understanding, Proceedings of the 14th International Conference on Engineering

Design ICED 2003, Innovation in Products, Processes and Organisations, Design Society, Linköping, Sweden.

Hansen, C. T. and Andreasen, M. M. 2001. Two Approaches to Synthesis Based on the Domain Theory. – Enineering Design Synthesis, Springer-Verlag.

Hekmatpour, S. and Ince, D. 1988. Software Prototyping, Formal Methods and VDM, Reading, Mass: Addition-Wesley Publishing Company.

Hindreus, T. and Reedik, V. 2002. Quality Dimension in Complexity Management of Product Development Interaction Patterns, Proceedings of International Conference NordDesign´2002, Norwegian University of Science and Technology, Trondheim, pp 129-136.

Hubka, V. and Eder, W. E. 1988. Theory of Technical Systems, - A Total Concept Theory for Engineering Design, Berlin Heidelberg, Springer-Verlag.

Kaljas, F. and Reedik, V., 1998, On Synergistic Aspects in Integrated Product Development of Mechatronic Systems, Proc. of 6th Mechatronics Forum International Conference MECHATRONICS’98, Skövde, Sweden, Pergamon, pp. 513-516.

Kaljas, F. 1999. Mehhatroonikatoodete tootearenduse iseärasusi. MSc Theses, Masinaehituse Instituut. Tallinna Tehnikaülikool, (in Estonian).

Keefer, D. and Verdini, W. 1993. Better Estimation of PERT Activity Time Parameters, Management Science, 39, pp. 1086-1091.

Krastel, M. and Anderl, R. 2001. Managing Mechatronic Simulation Models of Technical Products with PDM-systems. ICED 01. Glasgow., pp. 421-428.

Kusiak, A. and Wang, J. 1993. Decomposition of the Design Process. Journal of Mechanical Design 115(December), pp. 687-695.

Larsen, K., Pettersson, P. and Yi, W. 1997. UPPAAL in a Nutshell. Int. Journal on Software Tools for Technology Transfer. 1(1-2), pp. 134-152.

Malmqvist, J. 2001. A classification of Matrix-Based Methods for Product Modeling. Chalmers University of Technology, Sweden.

Malmström, J. 1998. Matrix Based Methods for Product and Process Structuring. Licentiate of Eng. Thesis. Machine and Vehicle Design, Chalmers University of Technology, Göteborg, Sweden.

McConnel, S. 1996. Rapid Development: Taiming Wild Software Schedules, Ch. 7: Lifecycle Planning, Redomond: Microsoft Press.

Morelli, M.D., Eppinger, S.D. and Gulati, R.K. 1995. Predicting Technical Communications in Product Development Organizations, IEEE Transactions on Engineering Management, vol. 42, no. 3, pp. 215-222.

Pahl, G. and Beitz, W. 1996. Engineering Design, A Systematic Approach, 2nd Ed. London: Springer.

Persson, J. G., Svengren, L. and Landqvist, J. 2003. Technology – Economy – Design: TED Integrated Product Development in Cross Disciplinary Teams. Proceedings of the 14th International Conference on Engineering Design ICED’2003, Linköping, Sweden, pp. 261-262.

Pimmler, T. U. and Eppinger, S. D. 1994. Integration Analysis of Product Decompositions. Proceedings of the ASME Sixth International Conference on Design Theory and Methodology, Minneapolis, USA.

Ringstad, P. 1997. A Comparision of Two Approaches for Functional Decomposition – the Function/Means Tree and the Axiomatic Appoach, Proceedings of the 11th International Conference in Engineering Design ICED´97, Vol. 2, Finland. pp. 57-65.

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

Salminen, V. and Verho, A. 1992. Systematic and Innovative Design of a Mechatronic Products, Mechtronics, Vol. 2. pp. 257-262.

Sauer, T., Berger, B. and Birkhofer, H. 2002. Describing Design Methods According to the Specific Needs of Users, Proceedings of the third International Seminar and Workshop, Zielena Gora, pp. 157-158.

Smith, P. and Reinertsen, D. 1992. Shortening the Product Development Cycle, Research-Technology Management, May-June, pp. 44 – 49.

Steward, D. 1981. The Design Structure System: A Method for Managing the Design of Complex Systems. IEEE Transactions on Engineering Management 28(3). pp. 71-74.

Suh, N. P. 1990. Principles of Design, Oxford University Press, Cambridge, UK.

Tähemaa, T. 2002. Assurance of Synergy and Competitive Dependability at Non-Safety-Critical Mechatronic Systems Design, PhD thesis, Tallinn, TTU Press.

Tähemaa, T. and Reedik, V. 1998. Reliability Criteria in Continuously Developing Mechatronic Systems, Proceedings of the 2nd Tampere International Conference on Machine Automation ICMA´98, Vol.2, Finland, Tampere, pp. 831-838.

Tähemaa, T. and Reedik, V. 2001. Prognosis of Competitive Dependability of Mechatronic Products, Proceedings of 13th International Conference on Engineering Design, Design Methods for Performance and Sustainability, WDK28, Professional Engineering Publishing, Glasgow, London, pp 3-10.

Ulrich, K. T. and Eppinger, S. D. 2000. Product Design & Development, 2nd Ed. McGraw-Hill, New York.

Unger, D. 2003. Product Development Process Design: Improving Development Response to Market, Technical and Regulatory Risks. PhD thesis. Massachusetts Institute of Technology: MIT Engineering Systems Division.

Vain, J. and Küttner, R. 2001. Model Checking – A New Challenge for Design of Complex Computer Controlled Systems, Proceedings of 5th Conference of Engineering Design and Automation (EDA), Design and Manufacturing Automation for the 21st Century, Las Vegas, USA, pp 593-598.

Vain, J., Kuusik, A. and Kaljas, F. 2002. Safety Verification of Degrading Mechatronic Systems. ICMA02, Tampere, Finland, pp. 615-622.

VDI 2206. 2002. Entwicklungsmethodik für Mechatronische Systeme, VDI-Verlag.

VDI-Richtlinie 2221. 1993. Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte. Düsseldorf: VDI –Verlag.

Wikander, J. and Törngren, M. 1998. Mechatronics as an Engineering Science. In: Proceedings of 6th Mechatronics Forum International Conference Mechatronics'98. Pergamon, London, pp. 651-656.

Williams, T. 1992. Criticality in Stochastic Networks, Journal of the Operational Research Society, 43, pp. 353-357.

Wyss, G. and Jorgensen, K. 1998. A User's Guide to LHS: Sandia's Latin Hypercube Sampling Software. Risk Assessment and Systems Modeling Department, Sandia National Laboratories.

APPENDIX 1

Curriculum Vitae

CURRICULUM VITAE

1. Personal details:

Name:	Frid Kaljas
Date and place of birth:	03.09.1972, Rakvere
Citizenship:	Estonian
Family status:	single, 1 child

2. Contact:

Address:	Rahumäe tee 6B-78, Tallinn
Telephone:	56 452 472
E-mail:	frid.kaljas@boschrexroth.fi

3. Education:

Tallinn University of Technology	1999	M.Sc. in Mechanical Engineering
Tallinn University of Technology	1995	Diploma Engineer in Machine Design
Rakvere Secondary School No. 1	1990	Secondary scientific education

4. Languages:

English	intermediate
German	intermediate
Russian	intermediate
Finnish	intermediate

5. Special Courses:

06-2000 – up to present	regular industrial automation trainings in Bosch Rexroth AG
11.1998 – 06.2000	regular pneumo - automaton trainings in Festo AG
10.1996 - 02.1997	Master's degree studies in ETH Zürich
08.1994 - 09.1994	designer practice in Landert - Motoren AG, Switzerland

6. Professional Employment:

06.2000 – up to present	Bosch Rexroth Oy	area manager, Estonia
11.1998 – 06.2000	Festo OY AB Eesti Filiaal	didactic manager
06.1995 – 11.1998	Avamax OÜ	sales manager

7. Scientific work / publications:

Kaljas F., Källo R. and Reedik V., Human Aspects at Design of Mechatronic Systems, Proceedings of the 9th Mechatronic Forum International Conference, Atilim University Publications, Ankara, Turkey, 2004 pp. 147-157.

Kaljas F., Källo R. and Reedik V., Realities in Interdisciplinary Systems Design, Proceedings of International Conference NordDesign 2004, TUT Publications, Tampere University of Technology, Tampere, Finland, 2004, pp. 251 – 259.

Kaljas F., Martin a., Tähemaa T. and Reedik V., Synergy Dimension at the Design of Interdisciplinary Systems, Proceedings of International Symposium on Machine Design OST'2003, Oulu, June 5-6, 2003, Raportti no 120, Oulun Yliopisto, Konetekniikan osasto, Oulu, Finland, 2003, pp. 138-147.

Tähemaa T., Kaljas F. and Reedik V., Assurance of Synergy and Competitive Reliability at Mechatronics Systems Design, Proceedings of the 2nd IFAC Conference on Mechatronic Systems, to be held in December 9-11, 2002, Berkeley, California, USA.

Vain J., Kuusik A. and Kaljas F., Safety Verification of Degrading Mechatronic Systems, Proceedings of the Fourth International Conference on Machine Automation: Human-Friendly Reliable Mechatronics, ICMA'02, September 11-13, 2002, TUT Publications, Tampere, Finland, 2002, pp. 615-622.

Tähemaa, T., Kaljas F., Martin A. and Reedik V., Indispositions at Interdisciplinary Systems Design, Proceedings of the 3rd International DAAAM Conference "Industrial Engineering – New Challenges to the SME, Tallinn, April 25-27, 2002, TTU Publications, 2002, pp. 66-69.

F. Kaljas, V. Reedik, On Synergistic Aspects in Integrated Product Development of Mechatronic Systems, Proc. of 6th Mechatronics Forum International Conference MECHATRONICS'98, Skövde, Sweden, September 9-11, 1998, PERGAMON, pp. 513-516.

Reedik V., Kaljas F., Tähemaa T., On Evaluation the Trends in Mechatronic Systems Design, Proceedings of the Second Nationational DAAAM Conference in Estonia SCIENCE´96, Tallinn, Estonia, 1997, pp. 89-93.

8. Supervised theses:

Synergistic aspects of interdisciplinarity of the automated systems at applications	2004	M.Sc. Rommi Källo

9. Research area:

Synergy-Based Design of the Interdisciplinary Systems

Tallinn,
21.04.2005

APPENDIX 2

Original publications

APPENDIX 2

Paper A

F. Kaljas, V. Reedik, On Synergistic Aspects in Integrated Product Development of Mechatronic Systems, Proc. of 6th Mechatronics Forum International Conference MECHATRONICS’98, Skövde, Sweden, September 9-11, 1998, PERGAMON, pp. 513-516.

ISBN: 0-08-043339-1

APPENDIX 2

Paper B

Vain J., Kuusik A. and Kaljas F., Safety Verification of Degrading Mechatronic Systems, Proceedings of the Fourth International Conference on Machine Automation: Human-Friendly Reliable Mechatronics, ICMA'02, September 11-13, 2002, TUT Publications, Tampere, Finland, 2002, pp. 615-622.

ISBN: 952-15-0861-2

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APPENDIX 2

Paper C

Tähemaa T., Kaljas F. and Reedik V., Assurance of Synergy and Competitive Reliability at Mechatronics Systems Design, Proceedings of the 2nd IFAC Conference on Mechatronic Systems, to be held in December 9-11, 2002, Berkeley, California, USA, Elsevier Science, Oxford, 2002.

APPENDIX 2

Paper D

Kaljas F., Källo R. and Reedik V., Human Aspects at Design of Mechatronic Systems, Proceedings of the 9th Mechatronic Forum International Conference, Atilim University Publications, Ankara, Turkey, 2004 pp. 147-157.

ISBN: 975-6707-13-5

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APPENDIX 2
Paper E

Kaljas F. and Reedik V., On Using the DSM Technology Approach to Synergy-Based Design of Interdisciplinary Systems, Proceedings of the 15th Conference on Engineering Design ICED ´05, to be held August 15-18, 2005 in Melbourne, Australia (peer-reviewed and accepted for publication).

This paper is prepared for publication signed.

DISSERTATIONS DEFENDED AT TALLINN UNIVERSITY OF TECHNOLOGY ON *MECHANICAL AND INSTRUMENTAL ENGINEERING*

1. **Jakob Kübarsepp**. Steel-bonded hardmetals. 1992.
2. **Jakob Kõo**. Determination of residual stresses in coatings & coated parts. 1994.
3. **Mart Tamre**. Tribocharacteristics of journal bearings unlocated axis. 1995.
4. **Paul Kallas**. Abrasive erosion of powder materials. 1996.
5. **Jüri Pirso**. Titanium and chromium carbide based cermets. 1996.
6. **Heinrich Reshetnyak**. Hard metals serviceability in sheet metal forming operations. 1996.
7. **Arvi Kruusing**. Magnetic microdevices and their fabrication methods. 1997.
8. **Roberto Carmona Davila**. Some contributions to the quality control in motor car industry. 1999.
9. **Harri Annuka**. Characterization and application of TiC-based iron alloys bonded cermets. 1999.
10. **Irina Hussainova**. Investigation of particle-wall collision and erosion prediction. 1999.
11. **Edi Kulderknup**. Reliability and uncertainty of quality measurement. 2000.
12. **Vitali Podgurski**. Laser ablation and thermal evaporation of thin films and structures. 2001.
13. **Igor Penkov**. Strength investigation of threaded joints under static and dynamic loading. 2001.
14. **Martin Eerme**. Structural modelling of engineering products and realisation of computer-based environment for product development. 2001.
15. **Toivo Tähemaa**. Assurance of synergy and competitive dependability at non-safety-critical mechatronics systems design. 2002.
16. **Jüri Resev**. Virtual differential as torque distribution control unit in automotive propulsion systems. 2002.
17. **Toomas Pihl**. Powder coatings for abrasive wear. 2002.
18. **Sergei Letunovitš**. Tribology of fine-grained cermets. 2003.
19. **Tatyana Karaulova**. Development of the modelling tool for the analysis of the production process and its entities for the SME. 2004.
20. **Grigori Nekrassov**. Development of an intelligent integrated environment for computer. 2004.

21. **Sergei Zimakov**. Novel wear resistant WC-based thermal sprayed coatings. 2004.

22. **Irina Preis**. Fatigue performance and mechanical reliability of cemented carbides. 2004.

23. **Medhat Hussainov**. Effect of solid particles on turbulence of gas in two-phase flows. 2005.