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REALITIES IN INTERDISCIPLINARY SYSTEMS DESIGN

Frid Kaljas, Rommi Källo and Vello Reedik

Institute of Machinery
Tallinn University of Technology
Ehitajate tee 5
19086 Tallinn
ESTONIA
E-mail: vreedik@edu.ttu.ee

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Abstract

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. A detailed definition of concepts of positive and negative synergy with examples from both categories is given. It is pointed out that the ever-growing competition on the markets has caused the need for radical cuts in product development time and has forced to change the approach to the design for reliability and quality of the non-safety-critical systems. As a result, negative synergy-based infant mortality risks are growing. It is also shown that synergy and quality indicators are in strong correlation forming a platform for competitive reliability. Special attention is paid to the clarification of interrelations between human and technical aspects in the design process. It is shown that human faults and mistakes can also be treated in synergy context. Further a search for synergy-friendly design strategy is provided and it is shown that the Design Structure Matrixes technology is a suitable basis for this purpose. Finally, some case studies of successful synergy-based integration of allied technologies are described. In the conclusion it is arrived at the truth that the synergy-based approach to the interdisciplinary systems design is a possible way to create a complete picture of all realities in design process.

1 Introduction

The increase of the integration of different technologies in new products with better 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. The concept of allied technologies is used for tagging these technologies that are integrated in the scanned interdisciplinary product. At the same time the design of interdisciplinary systems is a complicated activity as there is still no suitable design metatool allowing integrating technology-related design tools. However, some confusion can be noticed in the development of the comprehensive methodologies for interdisciplinary systems design as nowadays engineering design is not only a pure technical problem any more [Hansen&Andreasen, 2003]. Design is a complex activity, involving artefacts, people, tools, processes, organisations and micro- and macroeconomic environment (market, legislation, society) in which it takes place [Blessing, 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 expedient to be used in wider interpretation – as a generic model of activities, integrating design methods and procedures that are necessary for attaining the goal.

The practice of the design of interdisciplinary systems is characterized predominantly by an approach at which integrated systems are compiled from technology homogenous subsystems without a real demand for the development of a certain methodology of their closer integration. 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 chance to solve the problem [Tähemaa et al., 2001]. Synergy is here treated as an effect of suitable integration when the whole is more than the sum of its parts. 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. However, synergy is not only a technical problem, but involves also synergy between product development team members resulting in a successful or failed product. Synergy in man-machine relations in the process of use is just as important. The optimistic approach to that opportunity of synergy-based design is founded on the fact that there are a limited number of products available where the synergy of allied technologies is to some extent achieved. But the attaining of this synergy has still been more based on intuition or occasion rather than being the result of a systematic approach. However, the matter of the existence of outstanding synergistic products means that there must also exist the guidelines for the successful motion in this direction.

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 analyses 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 modelling and design methods, they appeared to be quite different. The repetition of the same analysis of design methods by the authors of the present paper about a decade later did not reveal any signs of coming nearer. It was even vice versa.

Nowadays interdisciplinary systems design decisions depend a lot on product customisation and also on the competition situation on the market. The ever-growing competition on the markets has caused the need for radical cuts in products 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 by involving also customers in the follow-up product development. Nowadays the methodologies of 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. On these grounds the Finnish National Competitive Reliability Programme for years 1995-2000 was launched giving also an impact on the present research. It is obvious that only a well-founded prognosis of optimal reliability makes it possible to select the ones from alternative

design solutions that are by price/reliability ratio competitive on the market [Tähemaa&Reedik, 2001].
The growing tendency of the integration of different technologies in interdisciplinary systems has also given a strong impact on the introduction of product quality dimension into design methodologies. Despite these developments the integration of the design methodologies of interdisciplinary systems with built-in quality and synergy lags behind the wave of the real integration of the allied technologies. Obviously product quality continues to be the key driver of the product development process. Despite efforts like TQM and ISO9000 they do not supply the necessary understanding of quality phenomena, which is the precondition for their use. Findings in industry show a fragmented picture of islands of efforts and a weak understanding of basic quality concepts [Andreasen&Hein, 1998]. In this context the role of human faults and mistakes in product development crops up 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.
Considering all the arguments described above it is clear that there is a growing need for a new integrating approach to interdisciplinary systems design. This approach has to make it possible to bring together all complicated issues of interdisciplinary systems design and to create a complete picture of all realities in design process. The authors of the present paper believe that one possible way out of the present situation may consist in synergistic approach to the integration of the different allied technologies in interdisciplinary systems.
The research results are to be presented in three sections. In the next section the philosophy of the synergy-based approach to the design of interdisciplinary systems is presented giving a necessary foundation to understand the following. In the third section the results of extensive research in human mistakes and faults at new equipment control and factory automation systems are given. The research methodology in the described sections is interpretation and generalization of the experimental data collected from the industry and assembled into databases. The last section is devoted to the search of a suitable framework for interdisciplinary systems design.

2 Basics of synergy-based integration of allied technologies

The main goal of the research in the interdisciplinary systems design is to propose methodologies for product development, helping to attain the maximum synergy of allied technologies. But at 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" mark the situation when summary effect of different factors due to their mutual empowering is greater then their sum. Sometimes it is called 2+2=5 effect. The essence of the synergistic approach to interdisciplinary systems design is seen in Fig. 1. As one can see it includes both hard (product) and soft (human) aspects.
Generic foundation of **positive synergy** is optimisation in its wider interpretation. During the whole history of engineering design one can notice the striving for the optimisation of the result. Historically the roots of synergy-based design lie in design for robustness and value engineering. A typical example of this approach is the family of design methodologies Design for X, which has been the most powerful set of the design optimisation tools during the last decades. The simplest way is logical optimisation, always used in 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 logically developed structure. So it is possible to assert that there are three ways of optimisation – physical, logical or analytical. In reality all the three approaches complement each other, calling forth total

synergy of performance. The precondition for granting physical synergy at the different technologies interaction 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 modelling and optimisation are powerful tools to save time and resources at experimental research and at the verification of the behaviour of logical systems [Vain&Küttner, 2001]. The art of success lies in a clever use of all the 3 ways to get a higher synergy of integration.

	Unsuitability of allied technologies Chain interface failures in one technology area cause failure in another technology area Failure of a component Miscommunication in human sphere Faults and mistakes in design process	Usual design where all allied technologies act independently and contacts between them are limited with harmonization of products' parameters	Compensation of mutual weaknesses of technologies and amplifying their common useful effects Physical, logical and mathematical optimisation Growing flexibility Multifunctional ability New functions not existing before	
100%				100%
	Time to failure	0	Profundity of integration (moving target)	
	Negative synergy		**Positive synergy**	

Figure 1. Positive and negative synergy deployment

To apprehend the philosophy of synergy integration better 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. Quantifying the synergy in artefacts proposes the existence of a synergy evaluation tool and universal scale to measure the products' performance. The scale of measuring may start from 0 for conditional interdisciplinary synergy-free product. So far for the evaluation of the positive synergy it is possible to use only relative parametrical scale based on the benchmarking the 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 the 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.

Anyway, 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 systems 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. 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. Physical reliability of the component or system can be treated as accumulation of negative synergy leading to failure and chain failure as the negative synergy between allied technologies. The experience with a large number of mechanical and electronic systems has shown that in general their failure characteristics follow a definite pattern [Rao, 1992]. A typical plot of failure rate versus time of a typical component is known as a "bathtub" curve and it is shown in Fig. 2. For the quantitative evaluation of negative synergy it is possible to use the metrics of reliability.

In order to clear up the roots of negative synergy a 5-year service statistics database for non-safety-critical mechatronic office equipment was completed. 4 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 350000 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 [Tähemaa&Reedik, 2000]. So 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 (see Fig. 2). 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% that is impossible to neglect. Due to the gradual upgrading of the product negative synergy effects are decreasing and the infant mortality period is nearing to the mature one. The key for reducing the negative synergy is to increase the synergy of teamwork during the design process and the team's core competence.

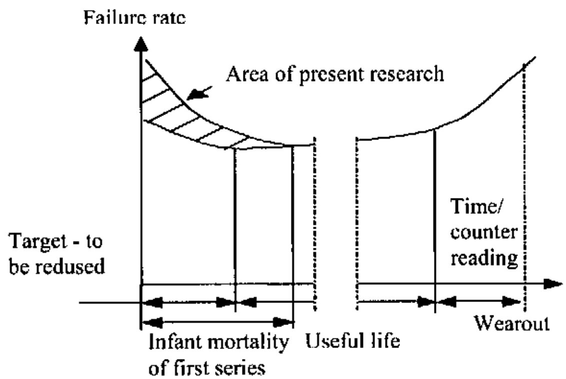

Figure 2. "Bathtub" curve of systems' failures

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 the attaining of better quality [Hindreus&Reedik, 2002]. The main difficulties related to the synergy-based treatment of quality dimension are associated with the matter that it is at the same time both a perceptual and a technical concept [Robotham&Guldbrandsen, 2000]. Concepts such as globalisation, mass customisation, product branding, e-commerce, total design suggest that consumerism is starting to be the leading philosophy shaking the summers of classical engineering design methodologies. 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. The quality assurance depends a lot on the organisational side of product development or, to be more exact, on the quality of human performance which will be discussed in the next chapter.

3 Human factors in synergy context

At the research of the effects of negative synergy at interdisciplinary systems design and application the causality of failures crops up. Wrong decisions of judgement and lack of skill were previously considered to be technical problems and were taken as a generic basis of the negative synergy. To bring clarity to these issues a special research was provided for two categories of systems: equipment control systems (more than 13000 cases) and factory automation systems (5 factories). An analysis of the compiled database gives a good chance to clear up the background of quality of human actions in engineering design. These data are very sensible and the authors regret that the companies involved cannot be revealed. To evaluate the validity of findings it is necessary to underline that the companies concerned are worldwide known contributors in the field of automation.

However, at first it is necessary to specify the terms used in further analysis. On the large scale all shortcomings revealed in the process of interdisciplinary systems application may be divided into faults **F**, mistakes **M** and technical problems **T**. Faults are the wrong decisions that have no justification. To the faults' category **F1** belong communication misunderstandings between the client and the design team or between design team members. To the category of faults **F2** belong all shortcomings connected with negligence. Mistakes have a far more complicated nature. To this category belong wrong decisions **M1**, caused by the lack of competence at synergy-based integration of different technologies. Another category of mistakes **M2** is conditional and is caused by unknown matters at the moment of the system's design and they may be cleared up in the further research or during the system's testing or use. A special category here is technical problems **T** where a component works 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.

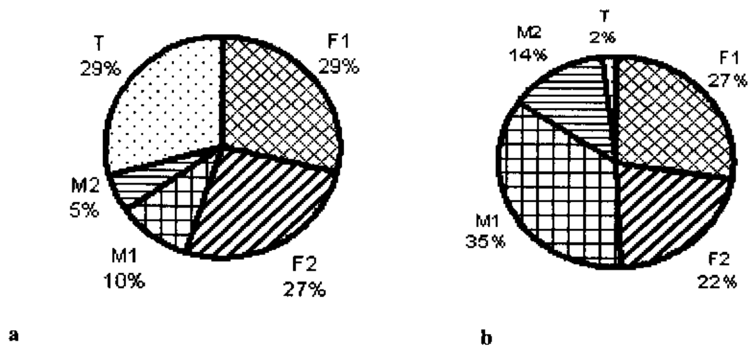

Figure 3. Statistics of human-based shortcomings at automation systems design and application

In Fig. 3a the statistics of the shortcomings analysis for equipment control systems design and application are shown. In the category of **F1** most of the faults are caused by misunderstandings as the client and designer may have different and sometimes fragmental picture about the control system and its parameters. In the category of **F2** the typical fault is the ordering of an unsuitable apparatus or an apparatus with wrong parameters. Mistakes in the category **M1** are caused by the lack of design teams' core competence in the technologies involved, as it is impossible to specialise in all of them. It is possible to sort out most of the mistakes of the category of **M2** during the system application process. The share of technical problems **T** is caused by infant mortality of the brand new products or low quality of the mature products. In the Fig. 3b the statistics of the shortcomings for factory automation

systems design and application is shown. This statistics includes both virtual and commissioning stages. The small share of technical problems **T** can be explained by the facts that before virtual testing most of the defective components are excluded. Faults **F1** are caused here by inadequate initial data, different proposals about components functioning, and late proposals changes by system real operators. Faults **F2** are usually of simple nature – mistakes at components installation, unchanged parameters at logical contours copying, conflicting signals, etc. These faults are mostly corrected by changes of application software. The causalities of mistakes **M1** and **M2** are the same as described above at equipment control systems.
Hence, it is obvious that nearly all shortcomings in the design and application process can be treated as synergy-based ones. Faults **F1** may be treated as a result of negative synergy in teamwork and **F2** as negative synergy in person inner communication. As the human-based negative synergy effects at the launch of automation systems increase the extra spending up to 5% to the system costing. The costing of the delay of production is usually much bigger. So it is worth taking measures to reduce the human risks.

4 A synergy-based approach to design

The main goal of the research in the interdisciplinary systems design is to propose methodologies for product development, helping to attain the maximum synergy of allied technologies. The basic idea here is the development of design methodologies of interdisciplinary systems as filtering ones having capability to let through and amplify the engenders of positive synergy and impede the spreading of negative synergy effects caused by the incompatibility of allied technologies. Despite all the precautions it is impossible to filter out all undesirable negative synergy effects as their appearance is a time dependent process and extends into the infant mortality period of the brand new product. In these conditions the way out of the situation is to grant the competitive reliability of the new product [Tähemaa&Reedik, 2001]. If to position the synergy-based approach to engineering design in classical product development environment, it introduces an additional dimension of integration to it. If to take into account the systems' theory approach the focus of the present research is on the area of transfer from the functions' domain to organs' one.
The design of interdisciplinary systems, which proposes allied technologies interactions analysis in the synergy and quality context is a complicated engineering task. In addition to this it is impossible to neglect the fact that interdisciplinary systems are going to be more complicated and there is a growing need to cope with the complexity parameters of products [Salminen et al., 2000]. The growing complexity of the product makes the management of their components' and chunks' interactions so intricate that a capable decomposing framework, suitable for representing all information flows in interdisciplinary products and procedures is needed.
If we take into consideration classical design strategies (sequential, cascade or spiral approaches) they do not include special tools for integrating different technologies. Much closer to the solving of the set up task are the new VDI2206 guideline for mechatronic systems design [Gausemeier&Moehringer, 2003] and the metamodels technology [Hallin et al., 2003]. The most suitable environment for design of the interdisciplinary systems seems to be the Design Structure Matrix (DSM) technology developed by Steward [Steward, 1981]. In this environment it is possible to decompose the product into components, to identify all the possible interactions between the components and, finally, to cluster the components into a system around their integration challenges. 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 [Eppinger, 1997]. On the product and organisational

level it is possible to show complex interactions between product components, their design process and supporting organization [Eppinger et al., 2001].

Considering everything that has been described above, it can be concluded that in order to keep the visibility of the whole analysis system, an approach should be found for handling the multiplicity of matrixes and their mutual patterns. In this context the DSM approach was used for research quality-synergy interactions [Hindreus&Reedik, 2002]. The quality-synergy matrix view was built up according to DSM technology rules, having 20 indicators of quality and synergy. The indicators were grouped in such a way that the first 8 represent the classical pillars of the TQM system. The next 6 have been appropriate to be classified into the category of products quality deployment and the last 6 into the pure synergy category. The earlier proposed quality and synergy correlation is quite impressive: on the medium level 67%, of which 10% can be classified as a strong correlation.

Coming closer to conclusions it is appropriate to ask if the synergy-based approach has given any useful results so far. In this context is suitable to look back on the roadmap of the research team. At the beginning of the 70ies the accuracy of interruptible sensors was about ±0.01 mm that was far not enough for building a pneumatic linear sensor. A time-consuming and thorough experimental research into the interaction of the laminar jet with interruptible scale led to the discovery of a new high accuracy aerodynamic effect. The essence of this effect is the local turbulisation of the jet to create a very sensitive balance of the forces sticking and tearing off the jet from the inclined scale edge. The discovered effect also allowed integrating the sensitive and the threshold elements already on the sensor's level, thus contributing to the achieving of this extraordinary accuracy. As a result, physical integration of solid mechanics and aerodynamics allowed raising the accuracy of the pneumatic interruptible type sensors about 10 times – up to ±0,6 μm and an original sensor was built [Neve&Reedik, 1975].

At the same time there was a deadlock situation with the accuracy of the pneumo-hydraulic servo due to the slow pneumatic signal transmission. The solution was found in the distributed control of on-off servo using the simultaneous signal transmission on sound velocity on different control systems levels. This early use of the dispersed control principles allowed to position pneumo-hydraulic drive with an accuracy of ±0.01 mm with one side positioning of ±0.0015 mm [Leschenko et al., 1972]. In the 80ies the distributed control turned to be a widely used technology.

At the beginning of the 1990ies synergy principles were successfully used in the research into the interaction of the air jet and elastic body (air massage of human tissues) getting better possibilities for heat exchange. Since the middle of the 1990ies the research has been focussed on the synergy-based integration of the mechatronic alliance that in the 2000ies was extended to the interdisciplinary systems.

Conclusion

While evaluating the 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 possible way to create a complete picture of all realities of the design process. 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. An analysis is provided for the separation of technical and human factors at equipment control and factory automation systems. As a result, a synergy-based approach to human faults and mistakes in product development process is developed. Further it is shown that DSM technology is a suitable basis for synergy-based design methodologies of the interdisciplinary systems. From the point of further research a new family of product development tools for the design of interdisciplinary products and systems with built-in synergy and functional quality is being developed.

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