SOCIO-TECHNICAL
SYNERGETICS

Vello Reedik

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Author/Editor

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ABOUT THE AUTHOR/EDITOR

Vello Reedik, Professor *Emeritus* at Tallinn University of Technology, Estonia, received his Diploma Engineer degree from Tallinn Polytechnic Institute in 1961, Estonia and his PhD (Candidate of Engineering Sciences) from the Moscow Power Engineering Institute in 1972. From 1968 to 1971, he took his doctoral studies at the Research Institute of Aviation Technology (NIAT, Moscow) under the supervision of Prof. V.A. Leschenko.

In 1961, he started his career at the Faculty of Mechanical Engineering, Tallinn Polytechnic Institute (renamed Tallinn University of Technology in 1992). In his academic career, he moved from Assistant, Senior Lecturer, Associate Professor to Professor in Product Development in 1997. In 1964-1965, he was guest researcher at the Laboratory of Hydraulic and Pneumatic Drives led by Prof. J. Prokeš at the Faculty of Mechanical Engineering of the Czech Technical University in Prague. In 1974-1975, as research fellow, he stayed in the Laboratory of Aerodynamics led by Prof. R.S. Neve at the Department of Mechanical Engineering and Aeronautics of The London City University, England, UK. In 2002, he was elected Professor *Emeritus* of Tallinn University of Technology, Estonia.

His main professional interest lies in the area of applied synergetics in the development of fluid engineering devices, robotic complexes and automation systems and their design methodologies. Milestones on this way are: pneumatic exact interruptible sensors, pneumatic backpressure sensors, sensing the robot systems, pneumatic massage devices, adaptive design methodologies for interdisciplinary systems, and chaos control for hierarchical teamwork. Along with research, V. Reedik was engaged in teaching students and course development in fluid mechanics, machine tools, robotics, mechatronics, system automation, and product development. In 2001, he was awarded the designation of EurIng – European Engineer.

PREFACE

The present book contains a systematized review of scientific research focused on the synergistic approach for solving different engineering tasks from 1965 up to today at Tallinn University of Technology, Estonia. Inherently collective, in this research, more than 80 master and 6 doctoral degree students have contributed under the supervision of the author. The research under discussion has been supported by grant-based financing and integrating industrial doctoral students into research.

When working as a guest researcher in Czech Technical University in Prague in 1964-1965 under the supervision of a leading scientist in hydraulic machines Prof. Josef Prokeš, the author started his studies of fluid mechanics. However, his interests were also in the synthesis of interdisciplinary systems based on the use of mathematical analogy in the mechanical, hydraulic and electrical systems. On this basis, he concentrated on the integration principles of different technologies. It should be mentioned here that in 1969, Prof. Hermann Haken in Germany formulated the principles of synergetics as a new field of science.

In 1968, the author started his doctoral degree studies in Moscow, NIAT (Research Institute of Aviation Technology) under the supervision of Prof. Viktor Andrejevitš Leschenko, a leading scientist in the area of hydraulic servos in the Soviet Union. He trusted a newcomer (the author) join and work in the sensor design team for the new fully fluidic NC (Numerical Control) machine tool. At that period, the fluidics control technology was on the peak of its use. At first, the research task seemed a mission impossible – to develop an advanced pneumatic interruptible jet type sensing element for a linear scale with five times higher accuracy than gained by that time in the world (in average ± 0.01 mm). After a 1.5-year intensive experimental research, the goal set was achieved and even surpassed at the accuracy (repeatability) of sensors' relay switching of ± o.6 μm. Later it became clear that success in this research was based on the discovery of the Ginzburg-Landau order or Haken's enslaving parameters synergy in the operation of a pneumatic sensor, which was reached experimentally. That was a first unaware touch of synergetics in the present research.

Though the goal set was achieved, the real physical nature of the discovered high accuracy aerodynamic effect was described only on the level of conjecture. The physical interpretation of this novel effect was clarified during guest research fellow work in The City University London, Faculty of Mechanical Engineering and Aeronautics, under the supervision of Prof. Ray S. Neve, a leading scientist in aeromechanics. For that research, an advanced experimental device was built and the sensing process was visualized.

Encouraged from successful research of interruptible jet sensors, further experimental research was enlarged to pneumatic backpressure sensors to raise their accuracy. The approach proved to be also successful and the resulting discovery of the aerodynamic resonance in the recirculation zone of this type of sensors made it possible to raise their accuracy for about 2.5 times.

At the end of the 1980s, the research activities were temporarily stopped, caused by the collapse of the Soviet Union and the restoration of the independent Republic of Estonia, which assumed full reorganization of university teaching. It was an intense period, with total dedication to organizational activities; scientific research was withdrawn on a standby position. But in the middle of the 1990s, experimental research on the employment of synergy was restarted with the study of the process of pneumatic massage to achieve optimal synergy of pressure and cooling effects.

At the same time, studies on empirical synergetics were initiated because of a growing need for new principles to integrate different technologies into interdisciplinary systems. On this wave, early doctoral research was initiated; PhD student Toivo Tähemaa explored the phenomenon of negative synergy effects between mechanical, electrical and software systems in office machines during their infant mortality period (Tähemaa, 2002). As a basis for that research, a database covering 3486 service actions of more than 1200 objects under inspection was completed. The focus was on the essence of negative synergy effects and principles of avoiding negative and empowering positive synergy.

In the early present century, the position expressed by the international engineering design community was that instead of rigid descriptive design methodologies, more flexible methods that take into account marketing conditions, human factors, and quality issues should be applied. Along with that wave, the research group focused on empirical studies of the reasons of “bad engineering”. The solid databases of human shortcomings were supplemented by relevant databases for light fitting design and production, equipment control system design and application, quality assurance system certification, and factory process automation system design and commissioning.

A novel methodology adaptive to design team capabilities for interdisciplinary system design was developed in the doctoral thesis of Frid Kaljas (Kaljas, 2005). This new synergy-based design methodology was successfully tested at the resuscitation of an uncompetitive pneumatic positioning system. Platform of this methodology is based on the symbiosis of Design Structure Matrix Technology and Theory of Design Domains. In this connection, the research team is gratefully acknowledging the kind help of Prof. Steve D. Eppinger research team at the Massachusetts Institute of Technology and the research team of Prof. Mogens Myrup Andreasen at the Technical University of Denmark.

In the next step, the research area was extended to problems of quality assurance using the market driven quality concept. As a result, a novel synergistic approach to the quality assurance process was developed in the doctoral thesis of Tiit Hindreus (Hindreus, 2009). A novel tool for the selfevaluation process was developed, which helps companies prepare to the certification procedure of their quality management system.

Then, in the doctoral research of Martinš Sarkans (Sarkans, 2012), the synergy-based design methodology was applied to modular products and robot systems in production. As a result, an early modularization principle for the design of mobile phone testing equipment was established. Next, the synergy-based methodology for modularized robot welding cell design was proposed and realized in practice.

The latest research period described in the present book contains the study of chaos control in hierarchical multi-agent systems applied for the design and commissioning of factory process automation. This research is based on the unique database of the statistical study of human shortcomings in the design and commissioning of 26 real factories. The doctoral study of Rommi Källo (Källo, 2016) addressed the above topic. Mapping the chaos process by deciphering it to chaos trajectories makes it possible to develop the synergy-based strategy for the fast tracking, hindering and blocking of the dissemination of human shortcomings. This meta-systems approach was successfully tested to prognoses the project implementation time and to find ways to its reduction.

The research presented in this book was conducted by the research group under the supervision of the author at the Department of Mechanical and Industrial Engineering (former Chair of Machinery Technology and Institute of Machinery), Tallinn University of Technology, Estonia. Continuous support with financing, research equipment and space by the home institution is gratefully acknowledged. The author would also like to thank the Estonian Science Foundation for financial support by three research grants during 1996-2004. The author gratefully acknowledges the kind help of our cooperation partners – Prof. Steve D. Eppinger's research team at the Massachusetts Institute of Technology and the research team of Prof. Mogens Myrup Andreasen at the Technical University of Denmark.

This book includes efforts of many research students and was composed as a result of close teamwork with supervised industrial doctoral students T. Tähemaa, F. Kaljas, A. Martin, T. Hindreus, M. Sarkans, and R. Källo. Finally, I would like to thank my family for their understanding and positive attitude during this time-consuming research activity. Special thanks to Siiri Reedik and Gustav Gerretz being my IT support.

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Tallinn, 2024

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1. ON ESSENCE OF SYNERGY

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1.1. Historical glace at synergy employment

The term *synergy* is derived from the Greek word *synergeia* and it means collaboration or co-operation. According to Oxford Dictionary, the word *synergy or synergism* refers to the integration or cooperation of two or more drugs, agents, organizations, etc. to produce a new or enhanced effect compared to their separate effects. The first known definition of synergy belongs to Aristotle who noticed that the whole may be bigger than the sum of its parts.

Looking back to the history of our planet, one can notice that synergy effects in the development of the nature are noticeable from its very beginning as a necessary coherence effect in the animate and the unanimated world. Observations of nature show innumerable examples of adaptability to surrounding conditions and mutual relations based on synergy. As a result, we are witnessing general striving to synergy-based natural selection.

From the beginning of ages, people have been trying to find synergy in their activities. Obviously, practical use of synergy effects in human cooperation can be observed in care of the next generation, home defence, raids to neighbours, big animals hunting, etc. The growth of synergy in these actions was based on the experience of effectiveness of interaction and teamwork. The body language, speech, literacy, and modern communication tools mark the milestones of synergy allocation.

One of the everlasting preconditions of human survival is getting food and its cooking. Cooking of food is inseparable from food aromas achieved by the synergy effect of different spices. Everybody knows that spicing is the big art and without overestimation, a special applied science (Birch&Campell-Platt, 1994). The same old tradition is the experience of the use of different natural herbs for the treatment of illnesses. During the treatment process, it is easy to come to the conclusion that some of the herbs empower the others' effect and vice a versa – can break down their impact. Nowadays we know it as drug synergy.

The trend to increase the synergy effect in mutual joint-work has been gradually transferred to the sphere of employment of different physical processes and development of the artefacts. The physical processes here cover the use by different ways of the wind or water energy. At the design of new machines or processes, the synergistic approach may be hidden behind some other terms such as rationalization or optimization. A good example here about optimization is the comparison of different ways of building the Eiffel tower in Paris. The original one is a steel construction. Due to the small tensile strength of concrete, the fully concrete tower of the same height looks like an Egyptian pyramid. The existing steelwork edifice is quite expensive, but if we use the synergy of concrete and pre-stressed steel warps or ferro-concrete, the result is a comparatively slim TV-tower.

We can meet synergy effects also in fine arts. Everybody has heard about Mona Lisa, the portrait of Lisa Gherardini painted by the Italian Renaissance artist Leonardo da Vinci in 1503. It is probably the most visited portrait in the Louvre Museum in Paris. What is the secret of its magnetic power? It is the synergy of colours integrating the beauty of the woman with her rich inner world. Everybody can exercise this type of synergy effect on its own when visiting the next room in an art gallery and letting the glance to fly over the pictures. Usually some of paintings nail your attention and these are on some level synergistic, which are worse for a closer study. You may encounter a similar effect on musical concerts where closing your eyes, pictures hidden in music arrive in your imagination. When you come out of the home museum of the famous Norwegian composer Edward Hagerup Grieg in Troldhaugen, Bergen, on a sunny morning and wonder the beauty of the mountains at sun rise, then probably you hear his wonderful Morning Sound in your ears.

To reach a higher level of synergy cognition, some fundamental philosophy and study of logical reasoning are required. The modern logic descends from the Ancient Greek philosophers Plato and Aristotle. The 18th century German philosopher Immanuel Kant argued that logic should be conceived as a science of judgement. All divisions of the logic: formal, informal, symbolic, and mathematical are valuable tools for the development of the synergistic way of thinking.

Looking back to the development and separation of different scientific trends, we can notice that the formation of a new and acknowledged science field is usually preceded by a long period of arrival of the fragments of this science. From the middle of the 19th century, the term synergy was used in the field of physiology for the concourse of actions between different organs in the health sphere (Dunglison, 1953). In today’s terms, regarding a training process in sport, we are aware of the entire amount of muscles to be trained in a synergistic way to reach new achievements. However, to achieve higher sports results as an addition of polishing the synergy of muscle action to the highest possible sight level, it is necessary combine all this with the reaction velocity of the neural system and the psychological readiness (Latash, 2008).

It is very important to understand drugs and their toxicological synergy. Drugs synergy occurs when drugs can interact in ways that enhance or magnify one of the effects or side effects of those drugs. Obviously, the reader is aware of the danger of combining depressants with alcohol, which causes exaggerated respiratory depression that can be fatal. Comprehension of toxicological synergy is important because chemicals that are individually considered safe might cause unacceptable health or ecological risk in combination.

In 1909, Lester Frank Ward defined synergy as the universal constructive principle of nature, including also social struggle and solidarity relations into the synergy sphere (Ward, 1918). When the social and human synergy is concerned, the main keywords are interaction and teamwork. Synergy in organizational behaviour means that teamwork will produce an overall better result if each person of the group is working towards the same goal individually.

The synergy allocation in economy opens different possibilities in competiveness, strategy and network identity. In this context, the keyword corporate synergy is used, which refers to benefits that the corporation expects to achieve when it merges with or acquires another corporation. The sights to synergy may be marketing, revenue, financial, debt capacity, tax benefits, etc. (Mantegna, 1999).

Thus, we can easily reach a conclusion that synergy phenomena are so ubiquitous in the natural world that by Ward's definition the synergy seems really to be a universal constructive principle of nature. This all paves the way to merge all knowledge and experience in synergy allocation into a new separate science. The first call to this was announced in 1950 by the Ginzburg-Landau theory (Landau, 1965), which concerns superconductivity physics.

1.2. Formation of synergetics as a specific science

As discussed above, synergy seems to be a universal constructive principle of nature; therefore, the field of synergetics use as science should be confined in some way. As a result, *synergetics* as a new interdisciplinary field of science was initiated by the German physicist Prof. Herman Haken in 1969 (Haken, 1983). When founding synergetics, Haken was inspired by the laser theory and he interpreted the principles of laser as self-organization of non-equilibrium systems (Haken, 2004a). According to him, synergistic effects are possible only in complex nonlinear systems that consist of many subsystems with an ability spontaneously to form spatial, temporal or functional structures based on self-organization. In terms of science, the cradle of synergetics is theoretical physics (Corning, 1995). Similar synergistic patterns can be observed also in chemistry, biology, medicine, psychology, economy, sociology, informatics, and engineering.

At the same time, the word synergetics was used by the American architect and designer Bukminster R. Fuller, known as the author of geodesic domes, who also used the term synergetics in the context of his geometry of thinking (Fuller, 1975; Fuller, 1979).

Let us have a closer look at Haken's science of structure or synergetics (Haken, 2004a). As mentioned above, the realization of self-organization requires a macroscopic system, consisting of many nonlinearly interacting subsystems. Depending on the external control parameters or their combination (environment, energy-fluxes, temperature, social conditions) in the described system, phase-transition with corresponding self-organization may take place. Firstly, the order-parameter concept was used in the Ginzburg-Landau theory to describe phase-transitions in thermodynamics (Landau, 1965). Haken generalized this concept as an "enslaving principle" where dynamics of fast-relaxing or stable modes is completely determined by "slow" dynamics of only a few "order-parameters" (unstable modes). In these conditions, self-organization obviously means an enormous reduction of degrees of freedom, which macroscopically reveals an increase of "order", but this macroscopic order is independent of the details of the microscopic interactions of the subsystem. Thus, synergetics takes into account deterministic processes as treated in the dynamic systems theory, including bifurcation theory, catastrophe theory as well as basics of the chaos theory and develops these to its own approaches (Haken, 2004a).

On the other hand, all systems are allocated to the influence of the environment, quantified as control parameters. If these parameters change, the system may adopt it qualitatively or smoothly. It is quite natural that in synergetics the main interest in theoretical physics is focused on qualitative processes (Haken, 2004b). In engineering, more attention is usually paid to smooth changes or quantitative processes (Bak&Chen, 1991).

In terms of mathematics, the order parameter equations are the stochastic differential equations. A very valuable contribution to synergetics is the book on complex nonlinearity: chaos, phase transition, topology change, and path integrals (Ivancevic&Ivancevic, 2008). This book is about prediction and control of general nonlinear dynamics of high-dimensional complex systems of various physical and non-physical natures. The value of this book is in integrating chaos, phase transitions, geometrical dynamics, and topology change to work together in the form of path integrals. In this connection scientific achievements gained by the Centre of Nonlinear Studies of Tallinn Technical University of Technology should be acknowledged. From the large spectre of their research, synergetics is supported by mathematical physics, complexity analysis, nonlinear wave dynamics, and biomechanics (Engelbrecht, 1997; Engelbrecht, 2015).

Besides qualitative changes described above, many models of coherent synergistic actions stretching from live cells to human societies exist. These levels can also be defined as examples of functional self-organization at interacting active agents of biological and social phenomena. In the overview of collective dynamic systems (Mikhailov&Calenbur, 2002), eight levels of synergistic systems are highlighted, differing by the level of complexity submitted to the interdisciplinary theory of complex systems. The first level of the systems is composed of agents that behave as automata with a limited number of responses and have relatively simple internal dynamics. In other words, these agents interact not fully expressing their complexity. This category, for example, includes heart muscle, excitable media, and fish schools. The second level holds systems the agents of which have capability of self-motion, for example, as bacterial flows, bird flocks, animal herds, and traffic flows. On the third level of the systems, attention is focused on noise problems and use of the processes in fluctuating media, which may be important in the evolution of the biological systems or social systems for accumulation of wealth and professional success. The fourth level consists of dynamic systems with delays and expectations. Typical systems of this category are age dimension, demographic waves, and market crash. The fifth level deals with mutual synchronization of systems. If the agents have cyclic internal dynamics, they may operate as clocks or oscillators; in some cases, they may be synchronized. The more refined kind of coherent collective dynamics consists of the formation of synchronously operating groups or clusters of agents, which is the focus on the sixth level. Keywords for this level are: logistic maps, neural networks, protein machines, etc. The dominant feature of the seventh level is the appearance of hierarchical organization. In the engineering point of view, it is a basis of any project organization. The highest level – the eighth – takes as a basis that dominant structures of the society are networks formed by individuals and their coherently operating groups. Through the various dynamical networks, a society can organize itself to perform certain required functions (Haken, 2004c).

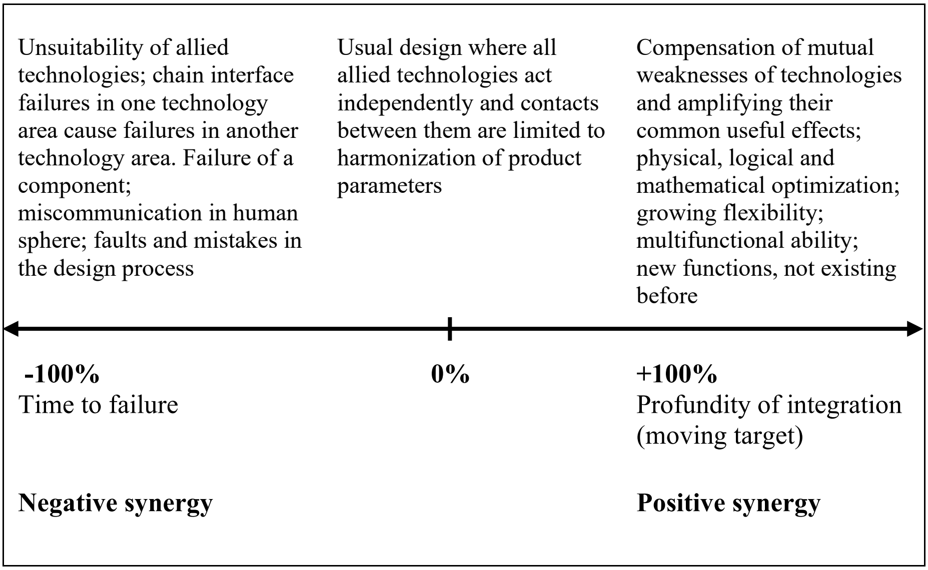
The question arises here – where the present book about socio-technical synergy can be mapped on this complicated scientific landscape. The first part of the book – experimental synergetics – belongs to the area of qualitative synergetics. Empirical research is mostly of the quantitative character; on the ladder of levels described above, it belongs mostly to its upper part, with the focus on hierarchical processes but has also some features of lower levels.

1.3. Evaluation of the level of synergy

When describing any phenomenon, it is always appropriate to pose a question about the measurement of its characteristics. Turning back to the Oxford Dictionary definition of synergy (see section 1.1), it is obvious that the effectiveness of integration is not equal to the sum of its separate effects. Mathematically, it means that $1+1+1 \neq 3$. This fundamental observation leads to a deduction that synergy as a phenomenon must belong to the nonlinear world. Further, it is obvious that synergy problems cannot be treated with scientific methods of reductionism as they reveal themselves only in complexity of nonlinear dynamics and may be followed by tools of computational intelligence (soft computing), integrating fuzzy technology, artificial neural networks, and genetic algorithms (Ivancevich&Ivancevich, 2008).

Clearly, there must be “something” to it that leads to a successful system integration, and we can call it (positive) synergy. However, sometimes we are witnesses of unfortunate integration, and so we may call it *asynergy* (negative synergy). Negative synergy may result in unfortunate piling up of unexpected inputs, leading a system to the situation of catastrophe. However, positive synergy also has a qualitative side, where changing the input parameters of the system results in dramatic changes in the system behaviour (see section 1.2). Naturally, when solving engineering tasks, all activities must be aimed at attaining the maximum possible positive synergy and pressing down negative synergy.

Thus, at first sight, it seems that synergy level is measurable by the brainwork done. Unfortunately, the result of the work and the amount of the work are not in definite correlation as professionalism and talent of actors have their influence. It is appropriate here to make deep obeisance to Leonardo da Vinci and Thomas Alva Edison for their multiple inventions. However, professionalism and talent solely cannot grant success. Sometimes the way to the right solution is paved by human faults and mistakes. Anyway, it is clear that the more professional the team is, the better are the chances to find the right way to a brilliant solution.



Unsuitability of allied technologies; chain interface failures in one technology area cause failures in another technology area. Failure of a component; miscommunication in human sphere; faults and mistakes in the design process

Usual design where all allied technologies act independently and contacts between them are limited to harmonization of product parameters

Compensation of mutual weaknesses of technologies and amplifying their common useful effects; physical, logical and mathematical optimization; growing flexibility; multifunctional ability; new functions, not existing before

Figure 1.1. Positive and negative synergy deployment for product design (based on Kaljas, 2005)

Let us discuss here the possibilities of visualization of the synergy effects using the framework of product development as a basis (see Fig. 1.1). It is clear from the previous discussion that synergy cannot be characterized solely by one parameter. The evaluation of the growth in the synergy level may be presented more clearly on the conditional scale -100…+100%. The synergy of -100% denotes a failure of the product due to its disability to function. A synergy level close to +100% is attained in safety-critical products for the space and nuclear technology. The 0-synergy level is theoretical as it is unrealistic to suggest that a professional designer or a design team is able to design a product without introducing their professional positive experience to it.

To meet the standards of space technology, product development will undergo an extensive process, which includes not only design efforts but also scientific research. On this way, there is an important zone of synergy level where the product meets the performance level of analogue products on the usual customer market. For non-safety-critical products, the optimization of the synergy level is market-driven and closely related to the moral aging and wearing of the products. In order to strike a high level of reliability, and therefore low service dependability, the cost of the product rises and it is difficult to sell. If the dependability is too high, the level of warranty costs rises, the service network must be expanded and the reputation of the organization may suffer. To guarantee successful business, it is necessary to find reasonable compromise between the previously described matters for the quality level of the products designed. In average, the cost of a top safety-critical product is about an order higher of consumer products. This is due to extra payment for efforts in the development and research to attain the product's higher synergy level. In other words, to obtain a successful product, it is necessary to find possibilities to empower the effects of positive synergy in the interaction of technologies and compensate the effects of negative synergy.

Let us look at the opposite side of scale ended by an ultimate limit of -100% where for multiple reasons, the product does not function any more or is not able to work at all from the very beginning. In most cases, a product reveals malfunctioning at testing. After imperfection removal and growth in the level of synergy, product performance can be obviously directed to the zone of positive synergy. At the beginning, a normally functioning product can move to the zone of negative synergy also at normal wear or accidental failure of some of its components. After the repair of the product, the performance of the product will be restored and it will able to serve on its duty. Naturally, beforehand, it should be found out if the repair is expedient or if it is to be changed for a new one, which is a usual problem to be solved with modern consumer products.

2. EXPERIMENTAL SYNERGETICS

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2.1. Development of the pneumo-hydraulic servo for high accuracy positioning

2.1.1. Search for synergy in an interruption-type fluidic position sensor

At the end of the 1960s, the fluidic control systems were very popular because of their higher reliability as compared to electronic systems. It should be mentioned here that a microprocessor was invented as far back as 1971. On the peak of fluidic technology progress in 1968, the author of the book joined the Scientific Research Institute of Aviation Technology (NIAT), Moscow, as a doctoral student. Research was supervised by Prof. Viktor Andrejevitš Leschenko, a leading scientist in the dynamics of hydraulic servos. At that time, he was participating in the development of the first Soviet fully fluidics controlled CNC machine tool. The newcomer (the author) was invited to join the research group working on the sensing system of that on-going project.

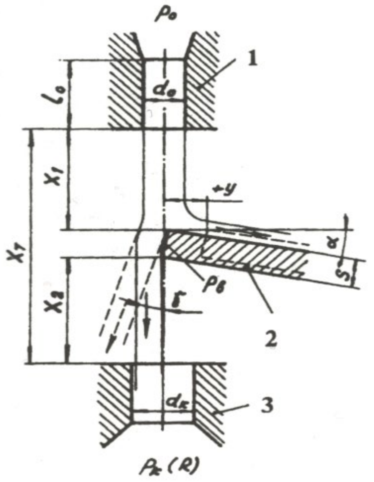


Figure 2.1. Pneumatic interruptible-type sensing element (Reedik, 1972)

It was necessary to design a linear sensor with an accuracy of at least ± 0.003 mm for the planned CNC machine. Such linear sensor in its exact positioning section needed an interruptible type sensing element (see Fig. 2.1) with comparable accuracy. In this sensing element, the air enters through the upper feeding nozzle 1 and after interacting with the penetrating scale 2, the modulated pressure is restored in the lower receiving nozzle 3. Importantly, up to that time, none of earlier researchers had come to an idea to incline the scale penetrating into the jet under the angle. In other words, all known research was completed at $\alpha = 0°$.

Next, let us take a closer look at the process of penetration of the scale into the jet. The jet flowing out from the upper feeding nozzle and not meeting the scale on its way reaches the output nozzle and restores the static pressure in it at approximately the feeding pressure level if the output nozzle is connected to closed room. If one or more fluidic elements are connected to the output nozzle, then the pressure depends on the aerodynamic resistance of their inputs. To get higher sensing accuracy, it is natural to use a laminar jet, as the turbulent one has too high original noise level. Due to the use of the laminar jet, for further use of the digital control system, the pressure level of the sensor output needs to be amplified by the threshold element with the relay output signal. When the scale is penetrating into the jet, the latter starts to incline the jet out from the output nozzle and pressure in it as the output signal starts to decrease in correspondence with the penetration of the scale. Even using a thin scale, the output signal is far from linearity and the turbulization of the inclined jet occurs. If to increase the scale thickness, instability of the signal is observed as the jet starts to stick and tear off from the scale edge. At further increase of the scale thickness, the process of sticking and tearing off becomes stable, and we get a relay output signal. However, the switching process has too large hysteresis with the corresponding scattering or pure repeatability of the switching points.

Thus, to reach the sight accuracy of switching ± 0.003 mm, a new approach and concept were necessary. Careful literature review revealed that accuracy ±0.01mm was the maximum for that type of pneumatic sensing elements at that time (Töpfer&König, 1961; Healey, 1964; Auger, 1965; Stahl, 1967; Sharp& McClinttock, 1968; Assmus, 1969; Leschenko et al., 1970; Wiedmann, P. 1972). Thus, at first sight, the development of an expected sensing element at such high accuracy seemed to be the mission impossible.

Intuitively, it seemed that in the room of sensor parameters, it is possible to discover some anomalous situation. To avoid the loss of accuracy caused by the threshold element on the output of the sensing element, the latter must be excluded. In other words, the sensing element must itself give a relay output signal suitable for further use in the digital control system. This feeble hope in those days was based on the Ginzburg-Landau order or Haken's enslaving parameters where a system's behaviour changes dramatically (Landau, 1965; Haken, 1971). Unfortunately, such search for synergy in technical artefacts and processes was expected to be quite accidental and needed good intuition and very much time. The classical experiment planning strategies could not be used as they exclude nonlinear dynamics and therefore also the synergy in the examined processes from the beginning.

In this hopeless situation, a hypothesis was set up that there must be a combination in the present sensor parameter room where dominating parameters calling forth dramatic qualitative changes in the aerodynamics of the sensor behaviour, which leads to a remarkable sensitivity growth of it. In that situation, it is sometimes necessary to have some key idea to solve the problem. In this relation, the author of the book has noticed an interesting effect when bathing a child between the washing brush edge and the water tap jet. It gave an idea to turn the scale under the angle and to study interaction processes on its edge.

Sizeable experimental research was initiated, covering the whole room of possible sensor parameters (see Fig. 2.1). The test rig was built on the basis of an accurate measuring microscope at the scale division 0.001 mm with the repeatability of the reading 0.0003 mm. Feeding pressure for the sensor was stabilized to ± 0.2% by the water column overflow with a bubble-killer invented for that purpose. A way to the solution of the problem was opened; however, about a year of intense experimental research was ahead before the most promising qualitative synergy change in the sensor's behaviour was reached.

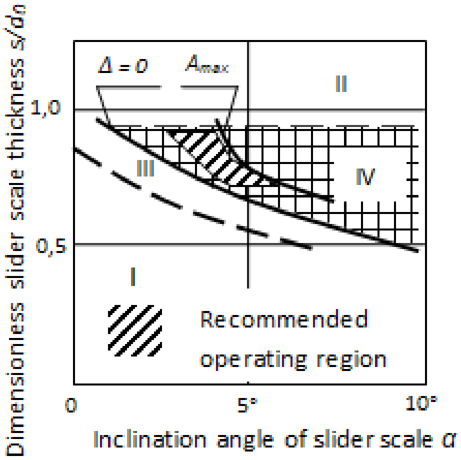


Figure 2.2. Areas with different statuses of the interruptible jet sensor's working regime (Reedik, 1972)
I – pure deflection (analogue output signal); II – high hysteresis of switching;
III – unstable tearing off and reattaching the jet to the edge of scale;
IV – high accuracy aerodynamic effect (relay output signal);
A_{max} – amplitude of the relay output signal

In a very limited combination of a few dominating parameters – the laminar jet, inclined scale and certain ratio of scale thickness to the laminar jet diameter – a tiny area IV was found where the so-called high accuracy aerodynamic effect occurs (see Fig. 2.2). The effect allows building sensors with unbelievable repeatability of switching σ (see Fig. 2.4) for that time ± 0.0006 mm (Reedik, 1970; Leschenko et al., 1972). In the outside view, the accuracy of this sensor is based on very sensitive sticking and tearing off of the jet from the inclined scale edge with a built-in threshold function into the aerodynamics of this process.

Fig. 2.2 shows an interesting combination of two ways to reach the qualitative synergy area. Closing to the high accuracy aerodynamic effect area IV from area II of high hysteresis of switching, the change of different self-regulation aerodynamic processes as a qualitative change is clearly evident. It is possible to treat the approach to area IV from the side of analogue signal I also as quantitative change of synergy. In summary, it was proved that the qualitative synergy landmarks – the Ginzburg-Landau order or Haken's enslaving parameters – can be found experimentally.

Next, we give a short review of the range of parameter combination to achieve an accurate aerodynamic effect. Nozzle diameter (see Fig. 2.1) d_0 was held in the limits of 0.5 to 0.65 mm and feed pressure at 1…3 kNm^2 , which gives a possibility to guarantee laminar jet and sufficient output power to switch over the fluidic amplifier. The distance x_1 should be chosen equal to 2-3 mm in order to eliminate the influence the acoustic noise on the end surface of the nozzle. It is suitable to keep the distance x_2 in the limit of 4.8 to 5.8 d_0 to catch the pressure leap at sticking and tearing off the jet from the edge of scale. For the same reason, it is suitable to keep the diameter of the receiving nozzle around $d_k = 1.4\ d_0$. The scale thickness s = 0.7 to 0.9 mm and the angle of the scale inclination $\alpha = +4°$ to 7° are the optimal limits.

2.1.2. Development of the pneumo-hydraulic relay servo

To solve the positioning accuracy, it was necessary to develop a pneumo-hydraulic drive for exact positioning. Combining the fluidic sensor measuring head, the fluidic control system, and an aviation hydraulic relay amplifier, it was possible to develop the first servo drive in the Soviet Union working close to the sound speed (see Fig. 2.3).

This drive is mounted on the planer machine tool bed and gives movement to its working table supported with the classical sliding guides. The hydraulic cylinder consists of additional cross-cylinders for changing the main cylinder capacity, allowing modelling the length of the driving cylinder. The relay mode hydraulic amplifiers with its pneumo-mechanic membrane transducer are fixed on top of the cylinder. The measurements of the transfer velocity of the control signal in this pneumo-hydraulic chain from the sensor to the driving cylinder proved that the control signal front travels close to the sound velocity.

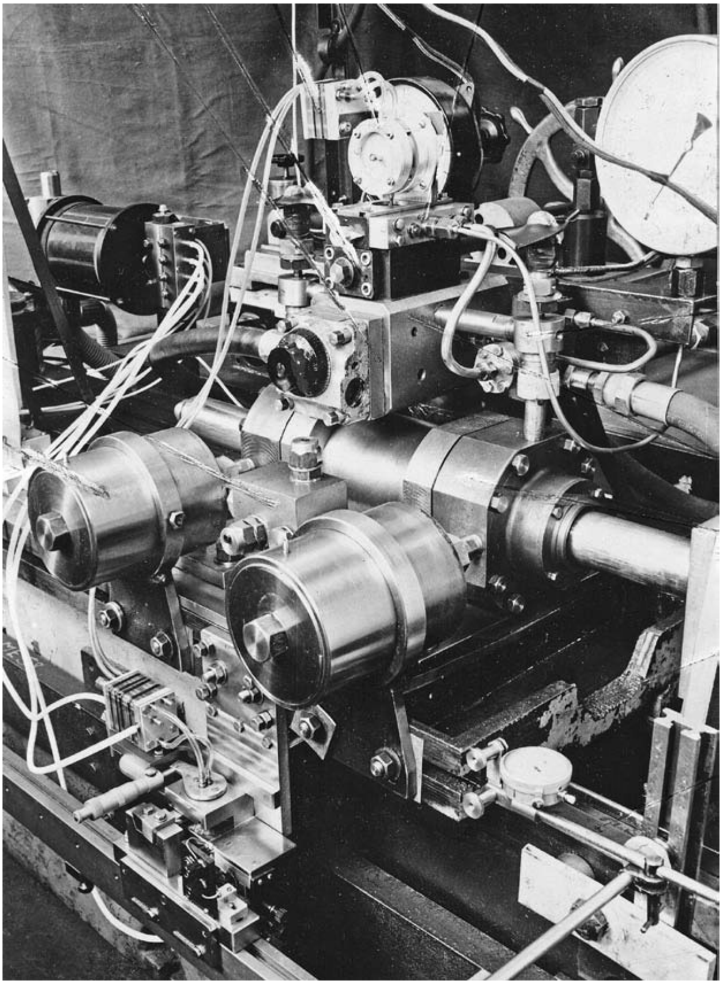


Figure 2.3. The pneumo-hydraulic experimental relay servo drive (Reedik. 1972)

The developed drive makes it possible to position the working table mass of 700 kg on at one-side positioning at the velocity of 1 mm/min with the repeatability of ± 0.001 mm. The latter is necessary to take as the limit in terms of repeatability σ (see Fig.2.4) as the final accuracy, as it depends mainly on the stability of movement on sliding guides.

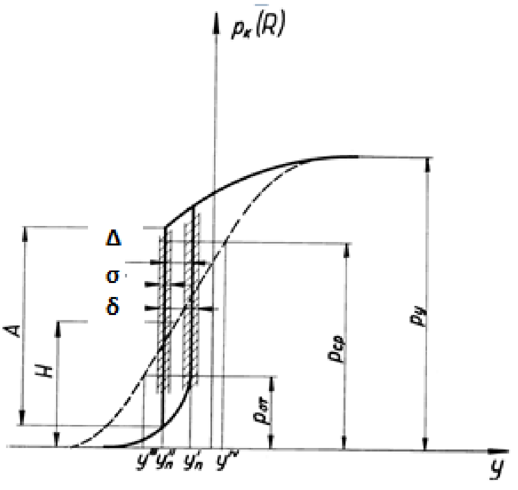


Figure 2.4. Output characteristics of the measuring head of the CNC machine tool (Reedik, 1972)

To use the drive in the servo regime, an experimental rig was equipped with a two-sensor turning head (Atlas et al., 1972). The left bottom corner contains the measuring head, its sensor block, and fluidic amplifiers (see Fig. 2.3). The drive's stabilization zone δ is regulated by rotating the head (see Fig. 2.4). This opens the possibility to study dynamics of the drive at different speeds of positioning. So, at the positioning speed 60 mm/min working on the two-side relay servo mode, the accuracy of positioning ± 0,01 mm was achieved. This was an acceptable result for our project. Later, this sensing head was used in the temperature control system (Reedik, 1982).

2.1.3. Visualization of the sensor's switching process

R.S. Neve, V. Reedik

Although the fundamental problem of the development of the new high accuracy sensing element was solved (see section 2.1.1), the nature of its aerodynamic background remained uncovered because of absence of relevant research. It was later, during joint research at The London City University when the essence of the accurate aerodynamic effect was finally opened.

The research of aerodynamics of the sensor was carried on in 1974-1975, during the author's work as a guest research fellow at The London City University, the Faculty of Mechanical Engineering and Aeronautics, under the supervision of Prof. Ray S. Neve. To study the nature of the exact aerodynamic effect in the Laboratory of Aerodynamics, a unique experimental stand was designed and built (Neve&Reedik, 1975). This stand was equipped with a high resolution camera and high-accuracy pneumo-electric transducer able to measure air pressure with an accuracy of ± 0.001 mmH_2O. The model parameters were chosen according to the principle of physical similarity, based on the Reynolds number. It means that after zoom of the real position sensor parameters 20x, the feeding pressure dropped down to 2.5 N/m^2. It is necessary to add that the experimental environment was surrounded with a cover and some pressure and velocity measurements were provided in a soundproof cabin and deadman regime. For visualization, the air flows of the paraffin smoke generator were used. But it was necessary to invent a possibility to reduce the diameter of paraffin steam from traditional 1 mm to 0.2 mm in that stand. After numerous experimental efforts, it was succeeded by forming the paraffin steam jet through the liquid paraffin ring with regulated temperature. The pressure in the scale surface was measured using the tapping holes.

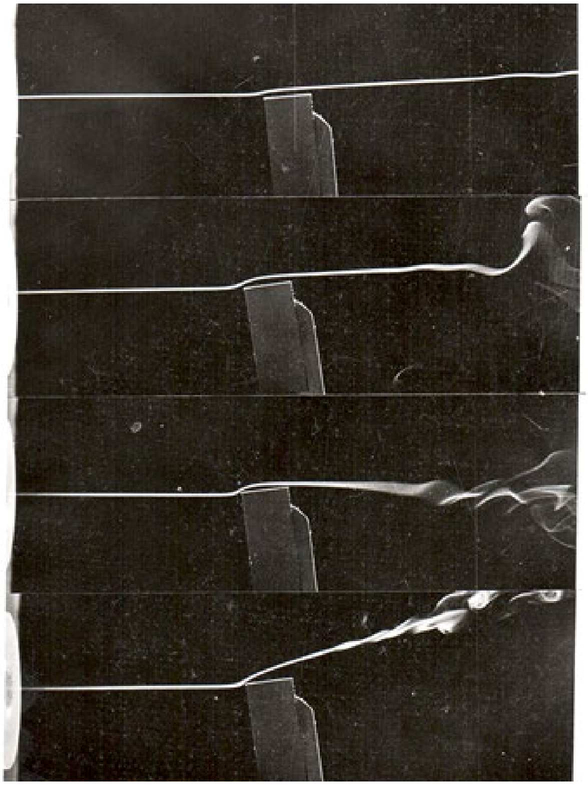


Figure 2.5. Visualization of the aerodynamics of the high accuracy sensor's switching process (Neve&Reedik, 1975)

As a result, the experimental stand enables visualization of the nature of the high accuracy aerodynamic effect (see Fig. 2.5). The jet of condensed paraffin stream represents only one and the most important flow stream of the whole jet tearing-sticking process. The figure shows that the described high accuracy aerodynamic effect appears due to very sensitive balance on the edge of penetrating into the laminar jet scale edge between sticking and tearing off of the jet aerodynamic forces. The sticking force at the centre of the jet is created due to local tubulisation of the core part of the jet and the tearing off force due to the impingement to the scale on the outer layers of the jet. In the further research, the real pressure distribution was measured along and across the scale to study the nature of pressure distribution acting in the process of sticking and tearing off of the jet. This provides the basis for the completion of the theoretical model of the interaction of the laminar jet and the inclined scale penetrating into it as well as for its graphical solution. The theoretical solution was close to reality (Neve&Reedik, 1975).

In summary, it was proved that by changing parameters flow and scale (as Hakens' order parameters of the macroscopic system), the self-organization of the switching process (see Fig. 2.2) can be reached, which is the fundamental attribute of the existence of synergy. At the same time, it is required to give evidence that the solution is very labour-consuming. But in the 1960s, there was no other way for research of the nonlinear world.

In a different way, the use of synergy is reached at the development of an exact positioning relay servo. All the preconditions of the traditional approach were firmly against reality to solve this task by a pneumo-hydraulic relay servo, not talking about usual guide surfaces and 700 kg mass to position. It was necessary to find a non-traditional behaviour of the drive in the relay mode of a servo working close to the sound velocity that is the macroscopic parameter for the system.

2.2. Experimental optimization of the backpressure-type fluidic position sensors

Encouraged by the success in the development of the exact fluidic interruptible jet sensors, our focus of the research shifted to the use of the principles of experimental synergy at the development of the proximity fluidic sensors. Due to the progress of microelectronics in the early 1970s, it was becoming ever more obvious that fluidics as low-power control techniques can be competitive only on the lower hierarchic structure levels of control systems where input-output devices are subject to the direct action of the severe working environment. In these systems, the proximity sensors (see Fig 2.6) based on focused or diverging annular jets were most widely spread. Attempts towards accumulation and generalization of state-of-the-art in the field of that type of fluidic sensors were confronted with the difficulties experienced by the dispersion and even contradictory results obtained by different researchers (LeHunte&Ramanathan, 1970; Zalmanzon, 1973; Wiedmann, 1974; Töpfer et al., 1978).

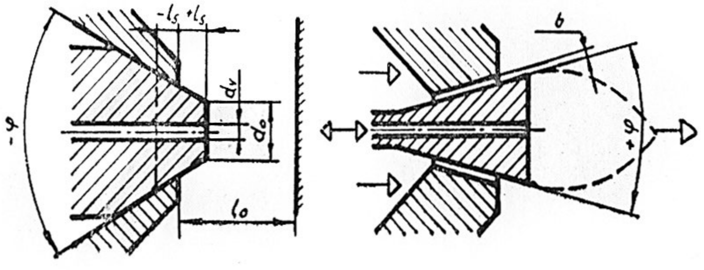


Figure 2.6. Focused and diverging annular jet proximity sensors (Reedik, 1985)

This situation encouraged the research team to make one more attempt to put together a data bank built up on unitary principles that would cover a large range of the proximity sensor parameters of diverging, cylindrical and focused annular jets. The main parameters of the sensor - the diameter d_0 = 5-16 mm and the angle of the jet cone φ from -90^0 up to $+60^0$ (see Fig. 2.6) were chosen to cover the common range of those used in commercially available sensors. The jet thickness of the jet b was planned to change in the limits of 0 to 0.6 mm. The set-back and set-off of the sensor's core ± l_s is an important parameter, which influence of the aerodynamic processes in the recirculation bubble, shown in Fig. 2.7 with an interrupted line. In the preliminary experiments, it was chosen in the limits $l_s = \pm 0.3\ d_0$. The construction of the experimental rig was universal for all combinations of jet diameter and jet angles, which is obtained by easy change of the sensor's core and case. Aerodynamic pressure and vacuum in the recirculation bubble of the sensor were measured by a miniature rotating medical injection needle that had a sensing hole on its side. In the composed pressure-vacuum diagram for one turn of the probe, it is easy to eliminate the probe's influence on the basic aerodynamic processes and to determine the velocity and direction of the flow as well as the overall vacuum/pressure in the examined point of the recirculation bubble.

The amount of experimental work was enormous but the efforts were worthwhile since the conditions of the existence of operating modes and the principles of choosing the sensor parameters were established. When an object of detecting is absent at the outflow, the sensor recirculation bubble forms (see Fig. 2.7). The bubble is formed by the vacuum ejected from the inner surface of the jet, and it is easy to feel it also by a finger.

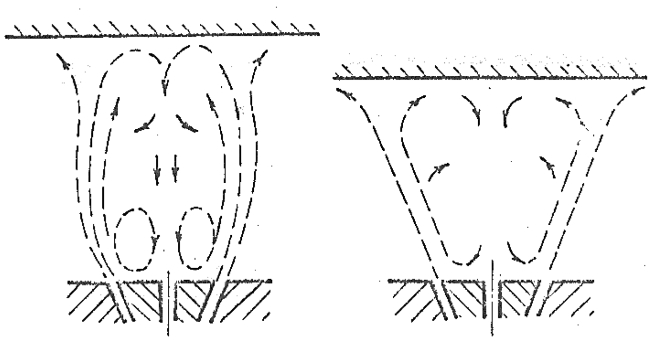


Figure 2.7. Flows in the recirculation zone before and after the relay switching of the diverging cone sensor (Reedik, 1985)

When the object is approaching the sensor (see Fig. 2.7), the recirculation bubble starts to distort due to an increasing backflow from the zone of contradiction with the object. This backflow reduces the vacuum in it and the streams in the bubble start to reorganize. Further events depend on the stability of the recirculation bubble. If its stability is low, then bubble break-up will spread over a long distance and on sensor's output, an analogue signal with inessential fluctuations will appear. At high stability of the recirculation bubble at object closing, a position may occur where the forces which act against those maintaining the bubble overcome the latter and cause the bubble to break. As a result, in that event, the relay output signal with hysteresis corresponds. At medium stability, the break-up of the recirculation bubble is accompanied by such intense fluctuations of the sensor output signal that the sensor turns out to be useless.

When choosing sensor's parameters, the main precondition is the mode of the aerodynamic process in the sensor recirculation zone. In most applications, the proximity sensors are used for the control of the existence of the object detected. Figs. 2.8 and 2.9 show the regions of different operation modes for diverging and focused annular jet respectively. This proves the initial hypothesis that synergy effects for this type of sensors exist and changing the system's macroscopic parameters, different areas with the self-regulation of aerodynamic processes occur. Detailed recommendations for sensor parameter selection based on the experimentally collected database are given in (Reedik, 1985). It is obvious that in most cases of use, the digital regime of work or the relay output signal of the sensor is recommended.

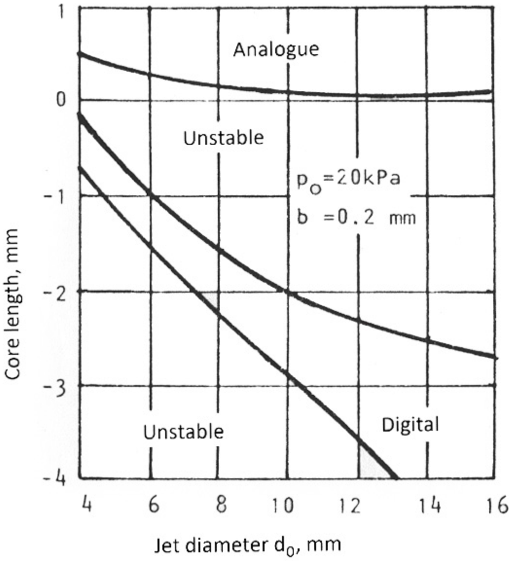


Figure. 2.8. Flow patterns at switching the diverging cone annular jet proximity sensor for $\varphi = 40^0$ (Reedik, 1985)

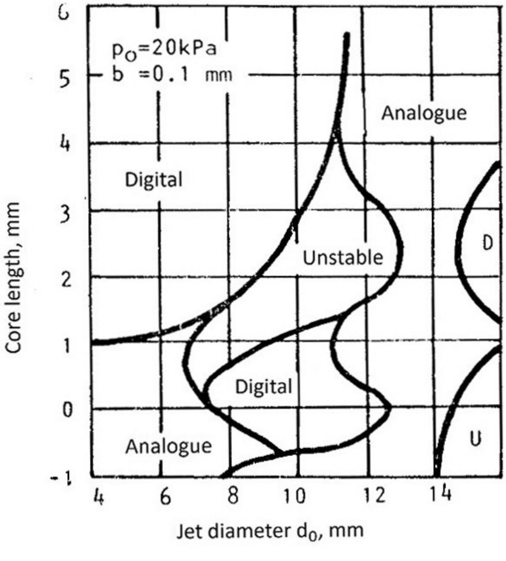


Figure 2.9. Flow patterns at switching the focused cone annular jet proximity sensor for $\varphi = -75^0$ (Reedik, 1985)

The accuracy of the relay output sensor is determined by the minimal stable switching hysteresis, which is some micrometres for miniature sensors up to 0.1 mm for the 16 mm jet diameter. In the range of the studied parameters of the sensor, the focused jet sensors are more precise, having repeatability of switching in the limits of 0.02 to 0.06 mm, as the repeatability of diverging ones is in the limits of 0.05 to 0.1 mm. An interesting aerodynamic effect was noticed – axial oscillation on the central part of the sensor around the switching point called the "aerodynamic resonance". This effect is the main factor influencing the stability of the process of switching of the digital sensor.

2.3. Development of triangular nozzle backpressure sensors

T. Hindreus, V. Reedik

In the 1970s, the first wave of the use of industrial robots in production automation started, and different types of pneumatic sensors were widely used for sensing in the robot systems. But for automation of the production of car safety belts stamped from the sheet material, the need of thin edge pneumatic detectors arose. For this purpose, the special triangular jet backpressure-type edge sensor (see Fig. 2.10) was developed (Reedik&Hindreus, 1993). As a result of experimental research, optimal parameters of these sensors were found to be of the same synergetic pattern (see Fig 2.12) of operating modes as at annular jet proximity sensors. But the whole picture is more complicated and depends considerably on the sensor's manufacturing accuracy.

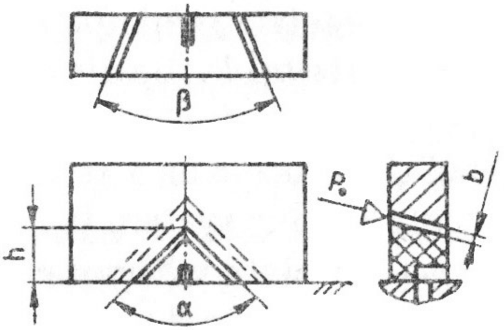


Figure 2.10. Triangular slot nozzle sensor for the detection of the edge of thin blades (Reedik&Hindreus, 1993)

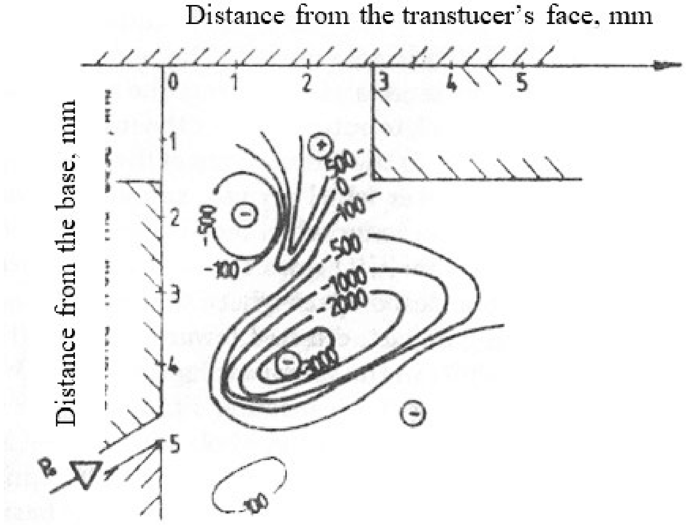


Figure 2.11. Pressure-vacuum areas in the sensor's recirculation zone before switching (Reedik&Hindreus, 1993)
α = 90°; β = - 75°; h = 5 mm; b = 0,2 mm; feeding pressure 20 kPa
Vacuum–pressure unit on the diagram regions is Pa

In the present case (see Fig. 2.11), two recirculation zones are forming, whereas the key role in the process of switching is played by the whirl between the closing blade and the output canal entrance. In the process of convergence of the object-plate, the picture of flows is gradually rearranged. The approaching object-plate restricts the flow more and more from the outer recirculation zone and the jet reflects back to the outer layers of the inner whirl, causing its strengthening. In the further process, the inner whirl moves closer to the sensors' face and finally breaks up and vacuum in the sensor's output changes to the pressure. But the real aerodynamic behaviour of the triangular jet sensors is very complicated and depends considerably on the object-blade thickness (see Fig. 2.12). It is difficult to achieve a pure relay output signal and so there is possibly content with close to the relay output at the streaked areas. In this case, the threshold element on the output of the sensor is necessary. The main privilege of this type of a sensor is the cubic form, which makes it easy to build it in technological equipment, especially into stamps. Triangular nozzle sensors were successfully used to control the stamping process of the details of automotive safety belts.

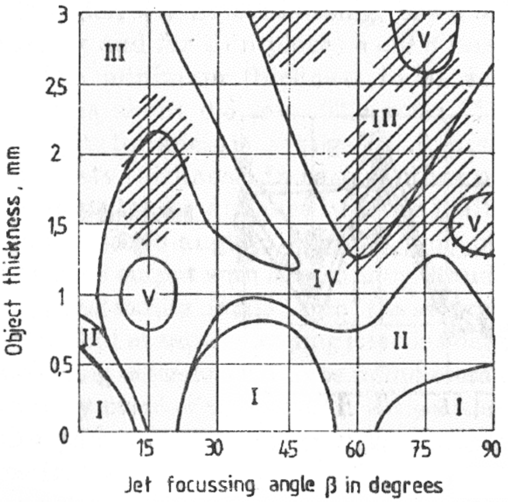


Figure 2.12 Operating modes of the triangular slot nozzle sensor at α = 105° (Reedik&Hindreus, 1993)
I – output signal fully in vacuum; II – too weak for use; III – close to proportional;
IV – several extremes with one switching point; V – several extremes with more than one switching point

Resulting from the study of proximity annular and triangular jet sensors, it can be summarized that experimental research has enabled conscious handling of all the processes in these types of sensors and establishing principles of their design. The contribution of numerous students involved in this experimental research is appreciated here. At the same time, it is easy to acknowledge that changing the macroscopic parameters of the sensor, it is possible establish areas where synergy patterns - modes of different self-regulation areas - can be found experimentally. This knowledge helps to achieve the maximum of performance and accuracy at the sensor design.

2.4. Research of air massage devices

Ü. Kristjuhan, A. Martin, R.S. Neve, V. Reedik, T. Tähemaa

Most people working in the standing position feel the fatigue of legs at the end of the work shift. Hydro massage with water jets has used to alleviate the situation (Polyakova et al., 1990), but this process of massage needs much room, water is splashed, and the devices may spread infectious diseases of the skin. Therefore, water massage is not popular among workers and the idea of changing water jet with that of air arose. Research on air jet massage for relieving leg problems of spinners and weavers was initiated by the cotton works Kreenholmi Manufaktuur, Estonia. Physically, at fatigue, temperature and dimensions increases of the legs muscles occurs (Kristjuhan, 1992).

From the synergistic point of view, the problem was to choose the massage jet parameters to grant most suitable synergy of action of the pressure and cooling in massage depression. For preliminary research, an experimental rig was built to determine the basic parameters: feeding pressure and diameter of the massage jet, jet attack angle, and distance of the nozzle (Reedik et al., 1995). Female mannequins were invited to participate in the experiments as male tissues appeared to be too stiff. On the basis of the preliminary experiments, an industrial massage device was built (see Fig. 2.13) and tested in industry. The massage device is similar to a chair, in which a person sits and stretches her leg at a convenient 45^0 angle. The shoe is left on and rests on a special support, restricting the sideways movements. The moving head equipped with air nozzles turns the lower leg automatically at 270^0 around and moves up and down. The whole surface of the calf is gradually covered by the action of the air jets. The full massage cycle (up and down) takes approximately 1 min and it can be stopped and continued in any position of the massage head. Comfortable massage pressure was 0.9 MPa and the diameter of the nozzle 4 mm. The results of the massage for 80 workers are described in (Kristjuhan et al., 1998). It should be mentioned that after 2-min massage, 100% of the subjects were positively surprised.

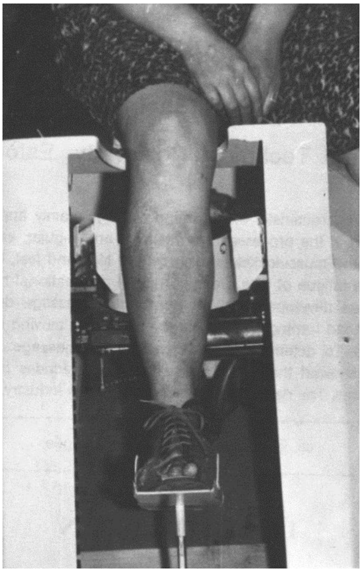


Figure 2.13. Air jet massage (Kristjuhan et al., 1998)

After successful industrial testing of the air massage device, it was necessary to optimize the parameters of the massage jets system or find other ways to reach maximum synergy of the pressure and cooling in the massage depression. During preliminary search of parameters for an industrial massage device, sizeable experimental research was already made. By that time, success in computational fluid dynamics had opened a shorter way to reach the goal of the research. Thanks to the kind help of Prof. R.S. Neve from the London City University, we could use the computational dynamics software package PHOENICS 1.4, which was an excellent tool for modelling the axis-symmetric tasks by the finite volume method (Martin et al., 2000). An additional problem was raised when modelling the massage depression on the human body in the conditions of changing elasticity. You get evidence of it by pressing your finger into your own leg. The solution was to use the software I-DEAS Master Series 1.3 able to solve this problem. Fig. 2.14 shows the velocity distribution in the massage depression. Modelling appears to be a much faster and easier way to reach the optimal solution of synergy in the massage depression.

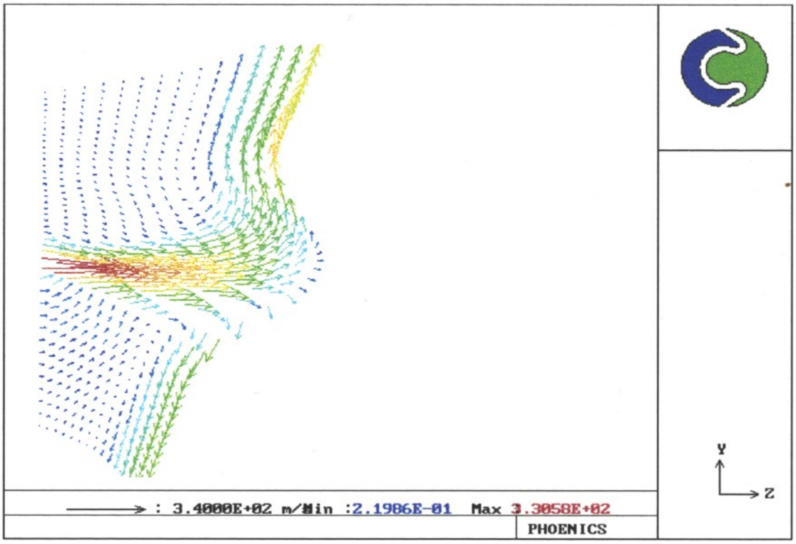


Figure 2.14. Velocity distribution in the massage depression at the jet interaction angle of 20^0 (Martin et al., 2000)

In summary, this was the last half-experimental effort of the research team engaged in the field of experimental synergy. In those days, it was only possible to do it experimentally; however, an enormous capacity was needed. Based on the experience collected, it was just the right time to open the door to empirical synergy.

3. EMPIRICAL SYNERGETICS

T. Tähemaa, V. Reedik

3.1. Empirical study of negative synergy in mechatronic products

3.1.1 Interdisciplinary attack to the classical engineering design

In the 1970s, the world market of industrial products appeared to be full; so for industry to survive in the hard competition for the market shares, radical cuts in the product development time appeared necessary. All this brought forth a need for a new generation of engineering design tools. Different schemes were developed for speeding up product innovation that had parallel, integrated and concurrent pattern of marketing, design, production, and financing. So an era of integrated product development started (Andreasen, 1993; Ottoson, 1996). Product development became the carrier of the technical innovation process, including all activities from the generation of ideas up to the launch of commercial production. Time-based competition became increasingly important as a strategic advantage in competition as well as a motive power to meet customer needs. But the priorities in the technological development in the society may be quite different and depend on the interest groups. One is clear – endless race to be the first with novelties is dictating the rhythm of progress and this meter is continuously shortening (Andreasen&Hein, 2000).

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 was set up as an ever-growing tendency. Mechatronics integrating mechanics, electronics and information technology was one of these growing technologies (Wikander&Törngren, 1998; Buur&Andreasen, 1990; Airila, 2000; Bradley et al., 2000). The term "mechatronics" was first used in the late 1960s at Japan's Yaskawa Electric Co. At the same time, the design of mechatronic systems was a complicated activity as no suitable design tools were available. The task to design the mechatronic systems would be much simpler if the design methodologies of its allied technologies are similar, but unfortunately, it is not so. Obviously, for suitable integration of allied technologies, the meta-tools that have a higher logical type and are viewed from a larger perspective are required (Mann&VanBussel, 1994).

Around the beginning of this century, the research community of engineering design reached a somewhat confusing conviction that the classical prescriptive engineering design methodologies are the past. It became obvious that engineering design is not any more a pure technical problem 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). It seems that the term design methodology is necessary to define in a wider interpretation context – as a generic model of activities, integrating design methods and procedures. As an example, a set of such tools is Design for X that has flexible, branched, and diversity pattern and opens a way for all-around optimization of design related to its favourite parameters or performance (Redford&Chal, 1992; Bralla, 1996).

In the launched race between the research groups to fill this gap, it seemed that one of the possibilities to advance in that situation was to involve a new paradigm – the synergy-based approach to design (Reedik et al., 1997). The synergy-based approach makes it possible to bring design parameters, market conditions, human factors, reliability problems, etc. under one umbrella. It is obvious that in this interdisciplinary mix, there is "something" more than these technologies offer alone. Examples are realization of the functions that did not exist before, increase of flexibility both during design and use (multifunctional ability), compensation of mutual weaknesses (synergy). Synergistic look at interdisciplinary system 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 product development problems (Tähemaa& Reedik, 2000b). Synergy is treated here as an effect of suitable integration when the whole is more than the sum of its parts. An optimistic approach to that possibility is based on the fact that there are a limited number of products available where the synergy of allied technologies is to some extent achieved. But this success has resulted from intuition or occasion rather than from a systematic approach. However, only the fact of existence of outstanding synergistic products implies that some guidelines for successful movement in that direction must exist. So when different technologies in a certain product are allied with the aim to compensate the weaknesses of mono-technologies, the grounds for calling forth positive synergy are created. In the case of unsuitability of integration and unfinished design, negative synergy may arise. In summary, the result could be positive or negative (see Fig.1.1.), and the problems to establish rules of this game are becoming topical.

The response to the research of negative synergy received on international conferences was hesitant due to the peculiar attitude to the term negative synergy. A possible reason may be in the practice of imagination that synergy is always something positive. On this ground, doctoral research of Toivo Tähemaa was initiated to distinguish the technical and knowable sides of negative synergy (Tähemaa, 2002).

3.1.2. From reliability to synergy allocation

When talking about reliability, it is first necessary to distinguish safety-critical and non-safety-critical systems. In safety-critical systems, failure of any component or subsystem is fatal. The definition of reliability generally accepted is as follows: reliability is the probability that a device is performing its function over a specified period of time and under specified operating conditions (Kleis, 1984). Design for reliability of these systems is developed up to the very high level and it is mostly because of the needs of space and military technology and nuclear power stations. Reliability engineering emerged as a separate discipline in the USA during the early 1950s (Tillman et al., 1980; Grosh, 1989; Doty, 1989; Henley&Kumamoto, 1992). For usual non-safety-critical consumer goods, it is appropriate to define the term of reliability as the probability that the user can get the expected result with the help of this equipment. So we can treat every call for help or service as a failure – non-performance or inability of the system or component to perform its intended function for a specified time under specified environmental conditions. All further research results described in the present book are dedicated to non-safety-critical products and systems.

Reality has shown that the reliability of interdisciplinary systems is more unpredictable as in mono-technological systems. Experience with a large number of mechanical and electronic systems has shown that in general their failure characteristics follow a definite pattern (Virtanen&Hagmark, 1997). While reliability allocation formulas for each of allied technologies are similar, the behavioural character of the components and systems differs. A plot of classical failure rate versus time of a component or system is known as a “bathtub curve”, shown in Fig. 3.1 (Rao, 1992). As a rule, for the mechanical system or detail reliability, the shape of “bathtub curve” is followed (see Fig. 3.1a). In the field of electronics, the infant mortality period is more complicated but the curve is still in force due to the changes in material properties and environmental influence (see Fig. 3.1b). It is clear that the wearout period for software cannot really exist and software failures in the computer program mostly clear up in the infant mortality period (see Fig. 3.1c).

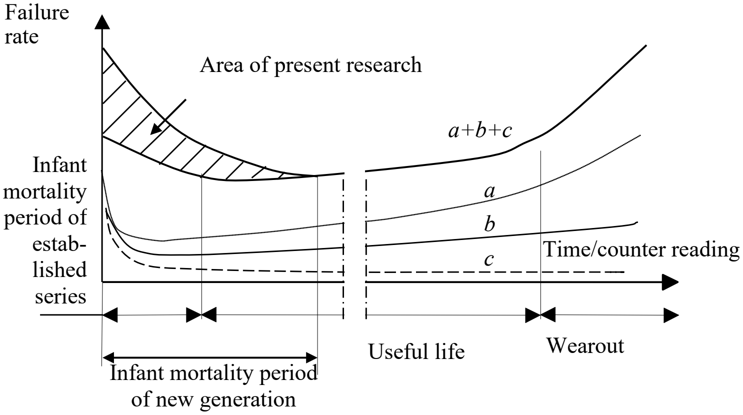


Figure 3.1. The research area allocation on the "bathtub curve" (based on Rao, 1992)

Since engineering systems consist of several components, the relationship between component reliability and system reliability must be understood. Service practice has proved that the sensitivity of mechanics, electronics and computer technology to various physical effects is quite different (Amasekera et al., 1997; Tähemaa&Reedik, 1998). Electronic equipment is very sensitive to overheating but software and mechanical parts can stand easily quite high temperatures. Electronic components and signals (electronics and software) are easily disturbed by small static charges while mechanical components are not. Mechanically moving parts are sensitive to dust while other system components are not.

Negative synergy effects have been known as chain failures. A particular component may fail as a direct result of some reason, or it may fail as a result of the chain failure caused by some other component of the system (Wikander& Törngren, 1998). Most of negative synergy failures usually clear up in the infant mortality period of a brand new model and their roots lie in the design process of new equipment.

When integrating reliability with maintainability and supportability, it is appropriate to use a more comprehensive concept of dependability (Virtanen, 1992). It is necessary to underline that reliability characteristics are universal and dependability characteristics are conditioned by the service network capability. The preventive maintenance and well-organized failure-describing network are the keywords to improve the seeming reliability for a customer (Hari& Weiss, 1999). Preventive maintenance is intended to eliminate costly repairs and special information net is needed to organize a continuously improving database to support the preventive and corrective maintenance.

3.1.3. Dynamics of negative synergy during the mechatronic product lifetime

In the doctoral research of Toivo Tähemaa (Tähemaa, 2002), the reality support was received from the database of non-safety-critical office equipment dependability collected in collaboration with a service organization and customer. The service database was completed in five years (1996–2001), containing models of office equipment of different generations (1992–1998). It consists of up to 3000 service actions solved in 2000 work hours with a total turnover of 350 000 EUR.

Analysis of the completed database shows that the moral and physical lifetime of mechatronic office equipment is roughly 4-5 years at medium intensity of continuous use. In average, the first year could be treated as infant mortality period, the next 2-3 years as useful life and the last year as wearout period. Fig. 3.2 shows the overall division of service reasons. It is clear that special interest in combined failures or negative synergy effects is real and is formed mainly from technical failures and therefore needs a further detailed study.

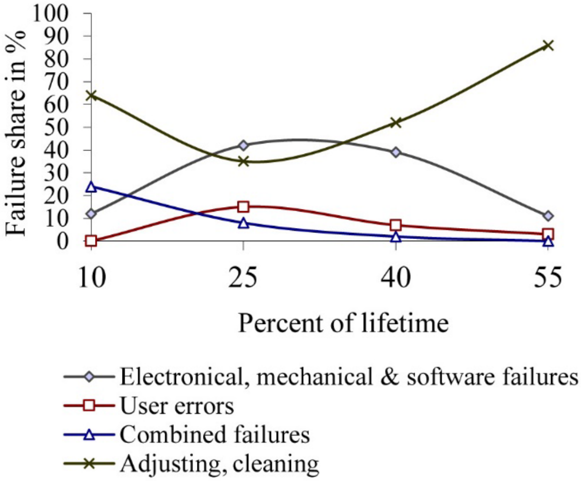


Figure 3.2. Overall failure distribution (Tähemaa, 2002)

Every new generation of office machines leads to a new failure distribution where the proportions between mechanical, electric, software, and combined failures vary. The failure distribution of a new model of 1997 during its first year use is shown in Fig. 3.3 when the model is still in infant mortality stage. Fig. 3.4 shows failure data for the same model in the useful life period.

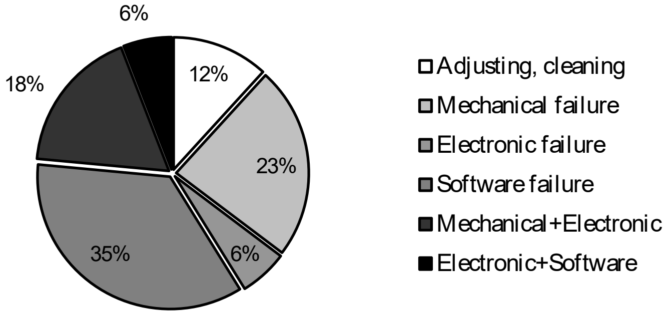


Figure 3.3. Failure distribution of the model since 1997 during the infant mortality period (Tähemaa, 2002)

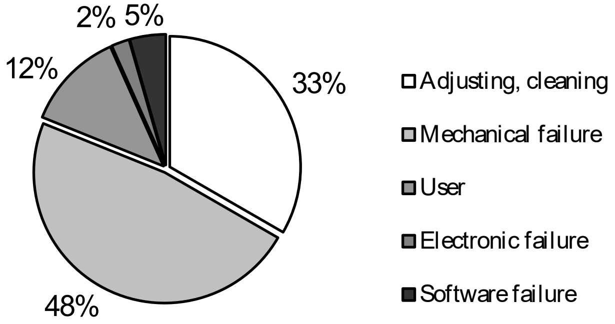


Figure 3.4. Failure distribution of the model since 1997 during the useful life period (Tähemaa, 2002)

The failure distributions above show that the producer has made remarkable efforts to remove the reasons of faults found in the service process during the infant mortality period. Further service attention is transferred to the period where the prevailing reason of failures is connected with the use of the devices.

Fig. 3.5 demonstrates the interface failures caused by dynamics of negative synergy; it is also evident that these are dominating in the infant mortality period of equipment lifetime in the brand new model. The share of mechanical and electronic failures is higher at older ones.

To understand the nature of interface failures or negative synergy, it is appropriate to list some typical reasons collected from the service field of office equipment: mechanical vibration in slides → damage of scanning lamp, pure contact or "cold" soldering → damage of electronic components or loss of the command transition, disoperation of the electronic temperature control of fixing rollers → damage of the rollers, malfunctioning of the movement limit sensor → damage of the driving motor or transmission, incorrect counting of the fixing temperature → blocking of material separation, failure in software → overburden of electronic components.

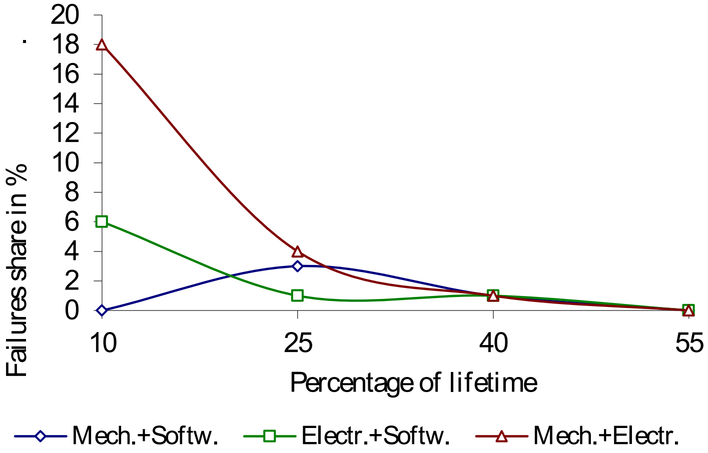


Figure 3.5. Dynamics of share of different negative synergy-based interface failures (Tähemaa, 2002)

For office equipment, the infant mortality period of the new model is prolonged approximately to 1/3 of its lifetime. For the modernized products where all synergy failures are eliminated, the infant mortality period lasts usually 1/5…1/4 of its lifetime (Tähemaa&Reedik, 2000a). Electronic software problems at a brand new model are solved after software updating; mechanical-electronic problems disappear when a certain amount of weak capacitors and scanning lamps are replaced. As a result, one can see that the synergistic failures as negative synergy are not a fiction but reality that has to be taken into account. But obviously, negative synergy has two basic reasons. The first one lies in the ineligibility of allied technologies and the second in the designers’ teamwork ability. The latter reason is analysed in the following part.

3.2. Negative synergy in teamwork

A. Martin

At the beginning of the present century, a new wave of research into human aspects in engineering design emerged. Up to that time, the focus had been basically on the psychological aspects of the designers' behaviour as individuals or team members. Very little data were disseminated about the quantified influence of human shortcomings on the full scale of engineering activities, starting from the early stages of design to the application and follow-up activities in new product development. Commonly, we call results of human shortcomings as "bad engineering" and there is an obvious need for more thorough study. Usual reasoning concerning the "bad engineering" involves mostly communication disturbances between the members of the design team, differences of persons' competence level and their physiological condition.

The driving force of the present research team was to find an effective approach to fighting against the so-called "bad engineering" in such sensitive areas that need the integration of engineering skill and knowledge from different fields of technologies. The first logic step in this research is widening from engineering design of mechatronic products to their production (Martin et al., 2006). It is necessary to underline here that all these data are a very sensitive domain and so for understandable reasons, the company involved is anonymous. To evaluate the validity of findings, it is necessary to add that the company concerned is a worldwide known strong contributor in its own field.

However, first it is necessary to specify the terms used in the further analysis. On the large scale (see Fig. 3.6), all the shortcomings revealed in the process of systems design and application may be divided into faults **F,** mistakes **M,** and technical problems **T**. Faults are the wrong decisions that have no justification. Communication misunderstandings **F1** between the client and the design team or between design team members belong to the category of faults. All the shortcomings connected with negligence fall into the category of faults **F2**. Faults **F1** may be treated as the result of negative synergy in teamwork and **F2** as negative synergy in personal inner communication.

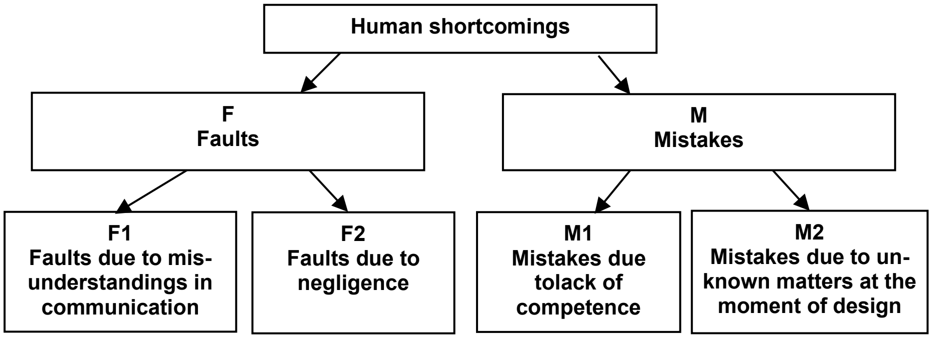


Figure 3.6. Classification of human shortcomings at the launch of a new product or system (based on Källo&Reedik, 2001)

Mistakes have a far more complicated nature. This category involves wrong decisions **M1** caused by lack of competence at the synergy-based integration of different technologies. As during the evaluation steps of a successive project, competent members of the team usually sort out individual mistakes, so as a summary, these mistakes depend mostly on the core competence of the whole team. Another category of mistakes **M2** is conditional, caused by unknown matters at that moment of time, which may be cleared up in further research or during the system testing and use. Technical problems **T** are a special category where a component is working poorly or does not function at all. In summary, it is obvious that nearly all human shortcomings in the design and application process of an interdisciplinary system can be treated as those synergy-based.

The following reality database was compiled for the analysis of human and technical shortcomings in the process of design and production of a mass product – light fittings. The scope of this database is 700 descriptions of human and technical shortcomings (Martin et al., 2006). Fig. 3.7 shows the distribution of human faults and mistakes along with technical problems. The dominating share, more than 75% of all shortcomings, relates to the area of technical problems. The main reason for technical problems is the failure of electronic components. These components work at high temperatures, but this is not the reason for failure, as they are designed to work in these conditions. The problem is that they are very sensitive to voltage fluctuations. As light fittings are installed in the process of building construction when electrical systems are still temporary and susceptible to large voltage fluctuations, it is difficult to protect them.

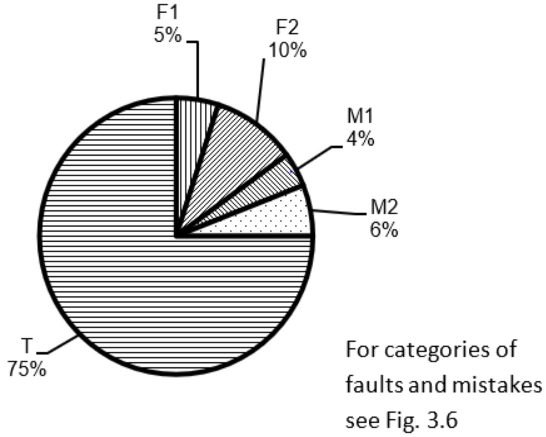


Figure 3.7. Statistics of human and technical shortcomings in the process of light fittings design, production and use (Martin et al., 2006)

From the human shortcomings side, problems are caused by the too large share of simple negligence faults F2. The main reason here is too high self-confidence or loss of attention and self-control at fatiguing repetitive work. Quite a high level of communication faults F1 can be noticed between the factory marketing and product development teams and between related factories. In the production sphere, the main source of communication faults is uncompleted documentation. Mistakes M1 due to lack of competence are trivial, as the factory is specialized in the production of light fittings and the staff are experienced and stable. However, some lack of knowledge in materials and electronics is perceivable. Mistakes M2 are mostly caused by lack of knowledge about the behaviour of electronic components material at high temperature.

The database for the evaluation of the human and technical shortcomings of engineering design and production must be treated as empirical or based on cognitive and interpreted experience. These data were collected statistically. How to use these random data to help companies to increase the productivity and efficiency of their business? To achieve this objective, the first step should be the analysis of possible similarity of mistakes and shortages in the upcoming design and production process. These databases are also a useful basis for prognosis of probable duration of product development and product dependability. They give usually help at the organization of teamwork and recruiting the personnel.

3.3. Prognosis of competitive dependability of mechatronic products

In the new consumer product development, the evaluation of its competitive dependability on the market is a serious headache. Figure 3.8 shows an appropriate decision-making playground. If you strike to the high level of reliability and take less care on the dependability, the cost of the product goes up and it is difficult to sell it. If the dependability is too high, the amount of preventive maintenance at warranty time goes up and the service net must be expanded and the reputation of the company may suffer. Success on the market with an attractive product with its outstanding properties can easily turn to the adversity when high exploitation costs or low reliability are discovered in the process of its use. It is clear that only with the market-driven dependability/price ratio (see striped area in Fig, 3.8), the product will be successful and ready for marketing (Jakobsen, 1995).

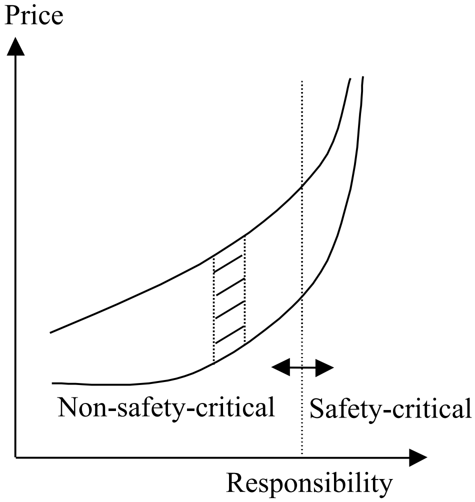


Figure 3.8. Decision-making playground for new equipment (Tähemaa, 2002)

From the 1990s, the mega-competition era has dominated where industry is operating continuously in the conditions when a new product is to be launched earlier than the previous one has proved its reliability and durability. The classical reliability concept that works well during the useful and wearout stages of the product life cycle has turned out to be ineffective to solve the problems of the infant mortality period of brand new product models (Tähemaa&Reedik, 1998). Failures caused by negative synergy occur practically during the infant mortality period of the new product life-cycle. Thus, the aim is to provide recommendations how to compress the striped area (see Fig. 3.1) resulting from the incompatibility of allied technologies or negative synergy as small as possible.

Now it is appropriate to return to the prognosis of dependability and demonstrate the use of the results of empirical studies of negative synergy. In today's competitive environment, product dependability, integrating reliability and maintainability determined by the capability of the service system are more relevant to the customer (Virtanen, 1997, Burns&Evans, 2001). All the recommendations here are applicable only to the non-safety-critical office machines; however, to some extent, they may be extended to other types of control systems.

For a producing company to survive, an adequate dependability prognosis and fast service feedback information about the product behaviour in the infant mortality period are vital. In this context, the failure database collected at service organizations as feedback from the user area is a necessary basis for reliability/dependability prognosis in the new product development process. A compiled service database is a producer's database and therefore anonymous.

In the following, an example of the prognosis of competitive dependability of a mechatronic product – a copying machine – is presented (Tähemaa&Reedik, 2001). Fig. 3.9 shows how to use the dependability information flow of the infant mortality period of previous products. The centre of the figure is a classical playground of the resource localization bordered by the determination and formation of the development costs, which are summarized as a curve of possibility affecting the costs. The fast feedback dependability information from the follow-up product development from the customer and service area is of great importance for the producer, enabling fast elimination of the effects of negative synergy at the brand new model (Extröm et al., 1999). Thus, it is suggested that the fast feedback from the market, straight from the end user to the product development team, must be organized in real time. So far, as a rule, the analysis of the primary data at the service organization has been provided and only statistic values are available for the producer (Gertler, 1998). Thus, it is reasonable to develop a widely spread event-based Failure Reporting and Corrective Action System (FRACAS) into the failures reasoning-based Fast Feedback Dependability Database (FFDD).

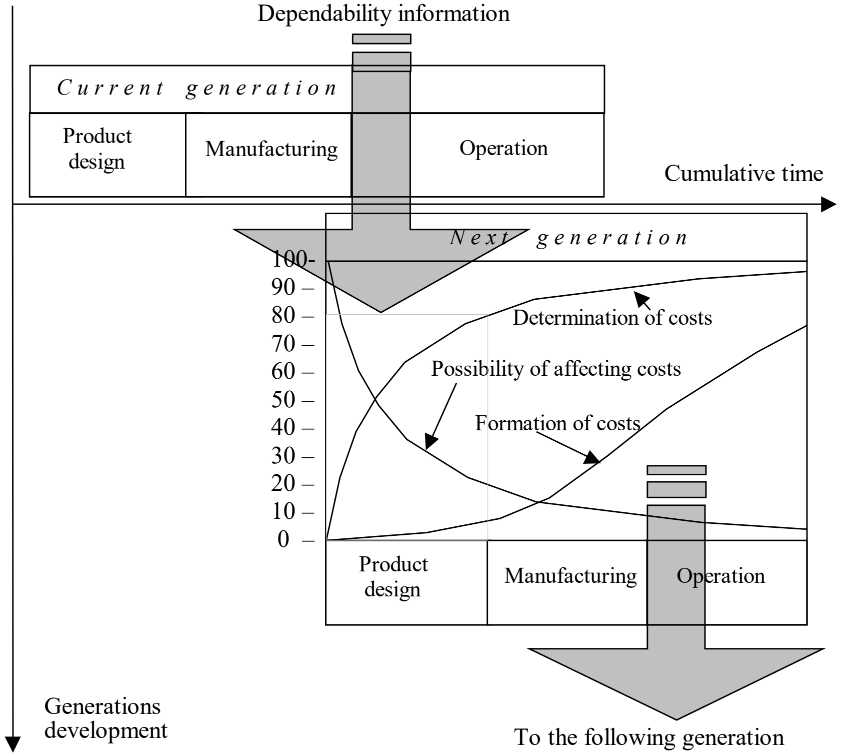


Figure 3.9. Possibility of affecting life cycle costs by early reliability/dependability information (Tähemaa, 2002)

FFDD is a useful tool for the product development team as well as for the customer and service dealer. From the producer side, FFDD makes it possible to observe dependability criteria, market shares and success level in every incorporated area all over the world and initiate operative corrections in the current model design or at the development of new ones. It contains also valuable information for the need of spare parts and makes it easier to eliminate illegal selling and servicing structures. From the service side, FFDD is a straight information flow, which avoids stepped intermediate links, helps to solve service problems faster, and makes a service organization feel as a team member.

Further methodology of the competitive dependability prognosis is used here in terms of wider interpretation as a generic model of activities integrating design methods and procedures with service data. In its essence, the prognosis of competitive dependability is an optimization task; from the mathematical point of view, choice of the target function is required. As in the present case, two parameters are important – product's dependability level and its price – it is appropriate to take the dependability/price ratio as a basis of optimization. For the prognosis of the dependability/price ratio at the design of a new generation of mechatronic office equipment, the following procedure is proposed:

1. Positioning of the planned product on the price/dependability playground
2. Specification of the degree of innovation of a new product
3. Planning of the product development process
4. Final prognosis of an optimal dependability/price ratio

Market analysis provided at the time of product development provides current approximate borders for both side of the playground, as shown in Fig. 3.8. Outside that area, your product seems to be too expensive or too unreliable. The problem is that the mentioned borders as a whole market are quite unstable and it is most profitable to operate somewhere near the borders inside the playground. But there are many other factors (advertisement, timing, political decisions, etc.) that can influence the selling results as well. For these reasons, it is impossible to use dimensions in Fig. 3.8, as it is always necessary to tailor for a certain market situation.

Specification of the degree of innovation is the most important stage in the new product development process, which has a vigorous impact on its dependability characteristics. Choice of the target customer group of the new product gives certain boundaries to the differences between the new and the old product. Bigger changes add more risks but in case of success, a stronger position on the market is guaranteed. In the context mentioned above, when starting new product development, at least three groups of details and modules should be distinguished: standard solutions, known or partly modified and totally new solutions. It is obvious that approaches to the prognosis of the reliability/dependability characteristics of the listed groups are different. For standard solutions, all the data necessary for the design for dependability are usually available. For the solutions partly modified, the dependability data are seldom fully available and it is necessary to find support from the failure database of similar solutions. At brand new solutions, background dependability information is absent. The novelties added to a new design are usually allocated to more detailed simulations and profound tests during the design.

The product development process of the non-safety critical mechatronic office equipment has to be planned in a traditional way (Ulrich&Eppinger, 1995). But the following funny definition should be useful to invigilate – product development is a continuous correction of existing errors with random fresh ideas, which unfortunately are the source of new errors. Despite curiosity of this definition, it underlines the fact that the level of innovations and the dependability rate are in close correlation. The most usual reason to start the development of a new product is the market pressure, as for example, competitors are introducing a new model with substantial innovations.

As far as prognosis of an optimal dependability/price ratio is concerned, it is necessary to take into account that during the last period, the term “price” has gradually lost its importance and the “life-cycle cost” is becoming more important. The life cycle cost of a product is strongly connected with dependability characteristics as it depends on the product procuring price, cost of spare parts and accessibility of well-trained specialists. Well-organized seeming reliability replaces the built-in one and makes the customer trust the producer as the dependability expenses for her/him are minimal (Beitz, 1997).

The prognosis of competitive reliability is clearly a mathematical optimization problem and for the prediction of the reliability; it is appropriate to use the dynamic programming technique developed by R. Bellman (Bellman& Dreyfys, 1962). Without plunging into details of counting, let us look here only at the evaluation of the results (Tähemaa, 2002).

The case study of the dependability prognosis of the copying machine from 1996 is based on the model from 1994, showing the number of copies without failing in average at the useful life period – 13,500. Without any changes in the concept of the main copier and sorter unit, the copying speed had to be increased by 25% and an automatic duplexing unit as a new function was added. Also, second paper cassette for a different size of paper was equipped. An automated document feeder from another base model was found suitable as an optional module for the fully automated two-side copy tasks. Real value of copies without failing in average of the new model was 10,600 at the infant mortality period and 13,000 at the useful life period.

To demonstrate the expediency of the proposed generic methodological approach, let us return to the period 1994-1996 and try to use the reliability prognosis for the model of 1996 again. The prognosis level of the dependability for the model 1996 was 11,900 cycles without failing, which is close to the reality, which was 10,600. Therefore, the task of the prognosis of the competitiveness of the new product through the dependability/price ratio is a realistic and useful task.

3.4 Empirical approach as a basis of synergy-based thinking

This chapter has mainly focused on the negative synergy when integrating different technologies at the same time taking into account human shortcomings in the organization of teamwork. Next, our interest will be in attaining positive synergy at the integration of technologies. The exploitation of positive synergy does not happen automatically; it is the result of a systematic approach to product development (Tähemaa et al., 2002).

When different technologies in a certain product are allied to compensate the weaknesses of mono-technologies, the grounds for calling forth positive synergy are created. In the case of unsuitability of integration and unfinished design, negative synergy may occur. So, the summary result could be positive or negative and the problems to establish rules of this game become topical. Sometimes it is really difficult to decide what really makes one product more attractive than the other. Some invisible properties, like auto adjustments, energy saving modes or readiness for instant run, give certain comfort in the use of a device, which you usually can notice only in case of their absence. These functions are mostly based on the synergy of different technologies; in this context, every new property of the system can be treated as a start of the new stage of competition.

We will now follow the development of allied technologies when the term "mechatronics" was first used in the late 1960s at Japan's Yaskawa Electric Co. (Ashley, 1997). During the first period of mechatronics development, the units of products were physically separated and a lot of space was wasted for layout reasons. Because of the low rate of integration, superfluous wiring, movement transfer, connectors, and other vain parts were dominating. At the computer control of electric motors, only the functional integration principle was used. But the reason of low reliability was not there; instead, at that time, failures in electronics were mostly dominating. Rigid software for running the basic operations was unshakable. Classical mechanics that had been mastered during a long time, worked without surprises. Strong efforts were made to develop the principles of new ideas and new solutions and the synergy of allied technologies remained practically out of consideration.

In the 1970s, mechatronics product development was concerned mostly with servo technology used in automatic door openers, vending machines, autofocus cameras, etc. Problems with processor speed and memory of devices were as boundaries in computer technology. Rapid development in the computer technology and in IC/ASIC electronics took place. The size of components decreased and first electromechanical units with embedded sensors arrived. Exactness and price of sensors and actuators led to new applications and first innovative devices for home and office were built.

In the 1980s when information technology was widely spreading, the use of embedding microprocessors in the mechanical systems was on the way to improve their performance. By the 1990s, communication technology was added to the mix, yielding products that could be connected to larger networks. At the same time, smaller and even micro-scale sensor and actuator technologies were used increasingly in the new products. Micro-electromechanical systems (MEMS), such as the tiny silicon accelerometers to trigger automotive air bags, are examples of high positive synergy.

Era of mechatronic office equipment starts from the second half of the 1970s and from that point on; it is easier to observe the development of the synergy of allied technologies. In his research (Tähemaa, 2002), made an attempt to derive positive synergy characteristics on the basis of non-safety-critical office equipment design, whereas he was looking back at two decades of their development. Some parameters of mechatronic office equipment, such as number of components, can be followed through all different generations of office machines (see Table 3.1). We can see that the increase of functionality has led also to the growth of the number of mechanical parts. At the same time, fast developments in the area of electronic components allowed a decrease in the number of electronic components. But as each IC or ASIC may consist of millions and millions of classical components, their real amount is increasing continuously. The growth of memory capacity is remarkable; for instance, read only memory (ROM) for the driving software has increased approximately 10% per year and buffer memory in the range of 5.5 Mb is quite usual today. Clearly, density of the components in the device has also increased many times; however, the weight is also decreasing and the dependability rate is even better.

Table 3.1. Dynamics of the structure of office equipment parts (rounded data)

Models	Mechanical parts	Electrical parts	Components of IC/ASIC x 100	Memory in Kb
1979	1500	3200	0	0
1989	2200	1600	2000	512
1999	4100	1500	10000	5500

In terms of quantitative characteristics of positive synergy, their dimensions and scale of evaluation have to be established. In the present case, it is suitable to use some general more or less stable parameters as background, such as the price of equipment at that time in constant DEM (from 1999 constant EUR). Clearly, the constant DEM-based evaluation of the consumer and producer price indexes is not an accurate basis. But as the producer price index for DEM for the same period has changed only 3.3% (International Financial Statistics, 2001), the inflation is really negligible. Positive synergy cannot be expressed as a sole universal parameter for equipment but rather as a set of parameters related to the product output parameters, such as functionality, operation speed, productivity, energy consumption, weight, starting-up time, and need for service.

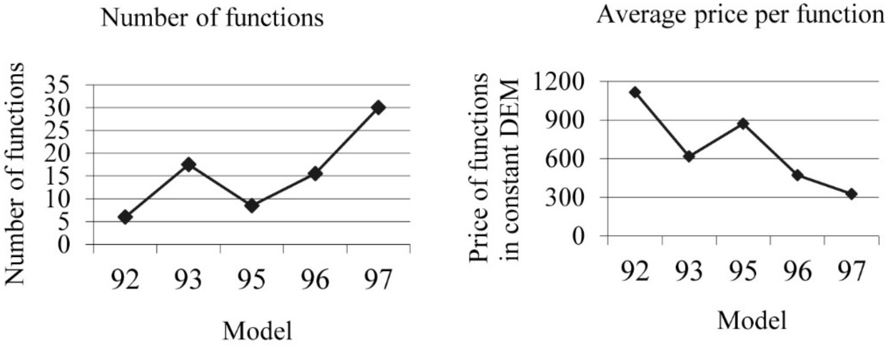


Figure 3.10. Dynamics of the number of office equipment functions and their cost (Tähemaa, 2002)

Fig. 3.10 shows the growth of functionality at different office equipment models. We can observe over-functioning on the 1993 models and under-functioning on the 1995 models. The latter was caused by erroneous reaction to the market requirements. Changes in the cost of functions are a clear sign of increase in positive synergy. Analysis has shown that the synergy index growth during the five-year period is around 3 in average. Synergy indexes for other output parameters for office equipment can also be determined in the same way: 1.3 – for operation speed, 2 – for productivity, 4 – for energy consumption at “stand by”, 1.4 – for weight, and 4 – for start-up time. On the basis of the change in the dynamics of these indexes, it is possible to take these trends into account at new device design.

A method suitable in the present context was proposed by Saaty (Saaty, 1994). As a basis of a customer survey, the degree of importance of the functions is evaluated. In our case, positive synergy is evaluated on the basis of three important parameters of office equipment: waiting time, duplexing volume and zoom ratio evaluated by a group of customers. The value scale from 1 to 9 is as follows: (1) equal, (3) moderate, (5) strong, (7) very strong, and (9) extremely strong. In the diagonal axis (see Table 3.2), value 1 is given because of the comparison between the factors themselves and the boxes below the diagonal contain inverse values of the value scale. For different customer groups, the weights vary noticeably; so the target group in the survey plays a remarkable role. Using this approach, the weights for three example parameters are found (see Table 3.2). On this example, the duplexing volume is most important, waiting time is on the second place and zoom ratio’s weight is the smallest.

Table 3.2. Weights of office equipment parameters

	Waiting time	Duplexing volume	Zoom ratio	Degree of value	Importance
Waiting time	1	5	1/3	1.19	**0.383**
Duplexing volume	1/5	1	9	1.22	**0.393**
Zoom ratio	3	1/9	1	0.69	**0.224**

As we can see, moving to bigger positive synergy is a very complicated process and needs high professional knowledge in allied technologies. But the “golden” rule of synergy-based thinking - pressing down the negative synergy effects and empowering the positive ones at technologies integration - is valid anyway. This is also the only way to move in the direction of the product dependability/price ratio optimal for marketing (see Fig. 3.8).

But this synergy-based thinking is valid also in a wider interpretation (see Fig.1.1) and also for safety-critical products. In this figure, the qualitative side of negative and positive synergy should be easily valued. We have shown that in terms of nature, synergy belongs to the nonlinear world and therefore there is no possibility that an official meter for synergy exists. So, the quantitative metering of negative and positive synergy is possible only on a relative or percentage scale. How is this concept related to empirical data received in the present chapter? The results of the above studies of negative synergy are all empirical, always based on the interpretation of the real facts in the design and production process. Empirical data from the past are a useful basis for prognoses. The aim of the prognosis may be to determine the dependability of the new products or the probable time and resources for their developments.

4. SYNERGY-BASED APPROACH TO ENGINEERING DESIGN

F. Kaljas, V. Reedik

4.1. Choice of strategic framework for interdisciplinary systems design

In the search for a methodology of synergy-based interdisciplinary systems design, a set-up of the objectives satisfying the conditions below were proposed (Kaljas, 2005). First, it has to be allocated to the perspective that will bring design parameters, market conditions, human factors, and reliability problems under one umbrella. Second, the synergistic look must be possible, allowing pressing down negative synergy and empowering positive synergy between the allied technologies. Synergy is treated here as an effect of suitable integration when the whole is more than the sum of its parts. Third, the possibility of continuous weighting synergy relations must be available. The existence of outstanding synergistic products implies that there must be some guidelines leading to successful movement in that direction.

Increased integration of different technologies in new products with improved functionality and marketing power has been lately an ever-growing tendency (Ulrich&Eppinger, 2004). Despite the developments, the integration of the design methodologies of interdisciplinary systems is far behind the wave of integration of the allied technologies. However, 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 methodological publication authors on engineering design support the strictly formulated prescriptive methodologies of product design, differing mainly in the iterations structure in the staged design process: sequential (Hubka&Eder, 1988; Suh, 1990; Pahl&Beitz, 1996); cascade (Smith&Reinertsen, 1992; McConnel, 1996; Ulrich&Eppinger, 2000; Cooper, 2001) or spiral (Hekmatpour&Ince, 1988; Gilb, 1988; Boehm&Bose, 1994). Without any doubt, these methodologies have provided basic guidelines at the design of many successful mono-technological products. It seems that the sequential approach is more widespread in mechanical engineering design, cascade at more complicated interdisciplinary systems and the spiral approach at software design (Unger, 2003). The minority of authors support a 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).

Classical design strategies usually include no special tools for integrating different technologies. The main shortage of engineering design methodologies is concentrating only on structural and behavioural aspects of the designed artefacts, not taking into account human aspects and market environment. In other words, most of the classical engineering design methods are purely academic.

From the viewpoint of information management, at the integration of different technologies, it is appropriate to classify product design methodologies into three categories: using parallel, from time to time or continuous treatment of allied technologies information (Kaljas&Reedik, 1998). Differences between these approaches are shown in Fig. 4.1. The widespread practice in mechatronics – integrating mechanics, electronics and information technology – at the beginning, was characterized by a subsystem approach, by which integrated systems are compiled from homogeneous technology subsystems without a real demand for the development of a certain solution for their closer integration (Wikander&Törngren, 1998). One of the most comprehensive comparative analysis of mechanical, electronic and software design systems was presented 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.

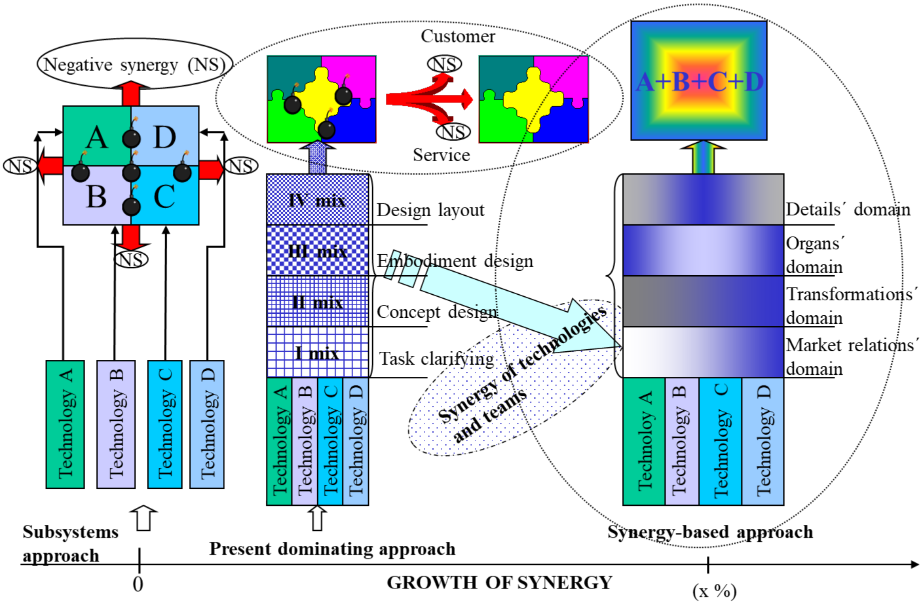


Figure 4.1. Strategies for the use of integrated technologies information (Kaljas, 2005)

The next and so far dominating practice is the use of decision-making steps allowing time to time information change (Gilb, 1988; VDI 2221, 1993; Boehm&Bose, 1994; McConnel, 1996; Pahl&Beitz, 1996). In this context, VDI 2206 guidelines for mechatronic systems design appear to be much closer to solving the integration task (VDI 2206, 2002; Sauer et al., 2002; Gausemeier& Moehringer, 2003). This approach belongs to a hybrid (from time to time) use of integrated technologies information and 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 those of more detailed, it resembles the spiral approach.

It has been a truly difficult task to move from the subsystems approach to synergistic design, as it is still prevalently an uncovered research area (Tähemaa et al., 2002). Running ahead on the way to increasing synergy allocation, in Fig. 4.1, the Theory of Design Domains (TDD) (Andreasen, 1980) is taken as the basis of the synergy-based approach, which seems to be most suitable when the marketing area is added (Fagersrtöm et al., 2002).

In the present context, an important question arose – where to allocate the remarkable number of product modelling and simulation methodologies. General type modelling software (Matlab, Simulink, etc.) is really technology-independent. At the same time, special modelling softwares are too technology-specific, without any tools for integration (Aarnio, 1999; Calderon, 2000; Krastel&Anderl, 2001; Vain&Küttner, 2001). One of the promising tools for technologies integration is the meta-model approach (Mann&VanBussel, 1994; Hallin et al., 2003), which includes systems theory approaches.

Thus, the growing need for the evaluation of the complexity of interdisciplinary products is evident (Salminen&Verho, 1992; Krishnan et al., 1997; Vain et al., 2002). 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 (or Dependency) Structure Matrix (DSM) developed by Steward (Steward 1981a). The philosophy of the DSM seems to be most convenient for interdisciplinary system design that has three steps of decomposition – integration. The first step documents the decomposition of the product into components. In the second step, interactions between the components are identified. Finally, the third step is 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 (Eppinger&Salminen, 2001). It was proved that DSM is a powerful tool for complexity analysis on the task level by structuring design into sequential, parallel and coupled tasks, whereas optimal iteration cycles are used.

In conclusion, it is clear that there is a growing need for a new integrating meta-approach for interdisciplinary system design. This approach should bring together all the complicated issues of interdisciplinary system design, creating a complete picture of all realities in the design process. One possible solution of the present situation may consist in the synergistic approach to the integration of different allied technologies. At first sight, it is appropriate to allocate the system theory approach for this purpose and to use the decision-making algorithm and stage the structure of the Theory of Design Domains (Andreasen, 1980). The second methodology worth integrating is the Design Structure Matrixes technology (Eppinger&Salminen, 2001), which makes it possible to describe visibly the synergy-based interaction between the system components and design processes of allied technologies.

4.2. Planning the platform for synergy-based design methodology

In the previous part, it was concluded that the most suitable platform for the design of interdisciplinary systems seems to be the integration of the Theory of Design Domains and the DSM technology. The DSM technology is really an effective system to realize the synergy-based approach for the presentation of product information. However, then it is required to integrate different DSM matrixes into the time- and task-dependent design process. When considering the design methodologies on three levels – problem-solving in general, the synthesis of technical systems and the total activity of product development, the Theory of Design Domains seems to be most promising.

The Theory of Design Domains proposed by Andreasen (Andreasen, 1980) is a capable tool for synthesizing complicated systems in a technology-dependent manner, moving the decision-making environment from abstract to concrete and undetailed to detailed direction in every stage of development. This system of engineering design provides for the control of the advancement of the design process in the 3-dimensional design space (see Fig. 4.2): undetailed-detailed, abstract-concrete through three views on the system – domains of transformations, organs and parts with many possible feedbacks. These substantial classes of structural definitions and behaviours of artefacts are based on horizontal and vertical causality chains. In this context, the Function-Means Tree as a graphical representation of the Vertical Causality Law is a suitable supporting tool. 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; Andreasen et al., 2015).

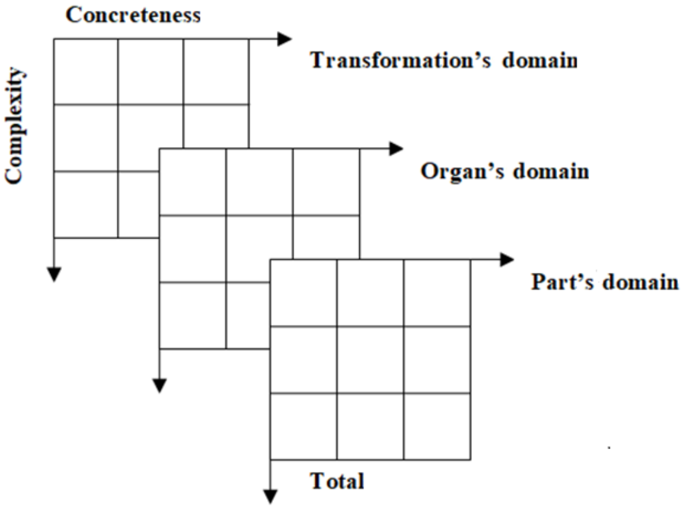


Figure 4.2. Design activities within and between three domains (based on Andreasen, 1993)

The DSM technology was developed by Steward (Steward, 1981b); and due to the outstanding capabilities of describing the interactions of system components, the use of the matrix methods has become more and more popular (Pimmler&Eppinger, 1994; Erixon, 1998; Suh, 1990; Clarkson et al., 2001; Malmqvist, 2001). Steward's DSM was empowered with static models, clustering analysis and some applications in the organization and product domain. 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; Rogers et al., 1996; Ringstad, 1997). The transformation of the matrixes makes it possible to involve scheduling and time dimensions into the design processes. A good classification of DSM was given by Browning (Browning, 1998) where the application areas of the matrix clustering and sequencing technology are presented (see Fig. 4.3), Utility in these applications stems from their ability to represent the complex relationships between the components of a system in a compact, visual, and analytically advantageous format.

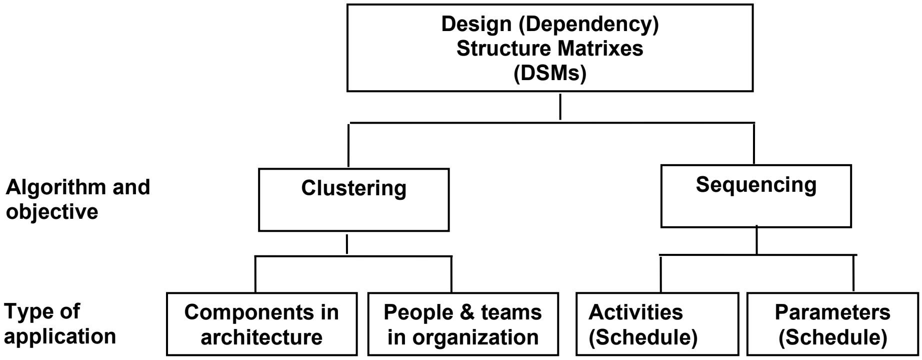


Figure 4.3. Classification of DSM types (Browning, 1998)

Component-based DSM documents interactions between the elements in the complex system architecture. This type of DSM provides us with the principle of taxonomy, which helps to weight them relative to each other. Coordination complexity can be significantly simplified if the elements are clustered or modularized so that their interactions occur predominantly within subsystems (Baldwin&Clark, 1998; Rechtin, 1991; Sanchez&Mahoney, 1997).

A team-based DSM captures the information flowing between individuals, teams, and/or other types of groups within a program. Here the goal is to identify the key organization interfaces and to cluster teams into groups or meta-teams where interactions are most frequent (Browning, 1998).

The key to building and analysing an activity-based DSM lies in understanding the concept of iterations and the differences between serial, parallel, and coupled activities. Figure 4.4 depicts these three activity types as time-based flows with their DSM equivalents below. A sub-diagonal mark in an activity-based DSM indicates information feed forward, while a super-diagonal mark exhibits information feedback.

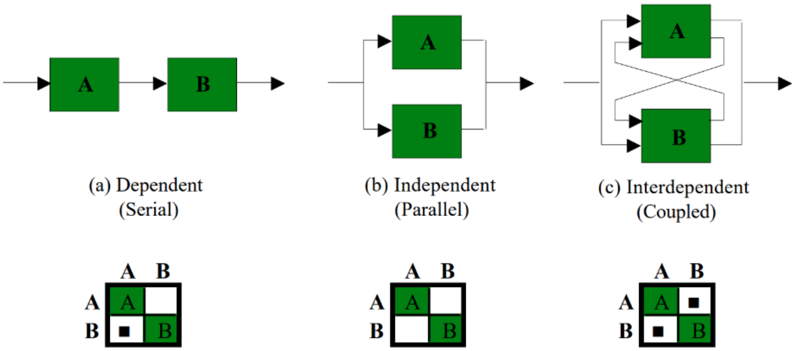


Figure 4.4. Three activity information flows and their DSM equivalents (Browning, 1998)

Figure 4.5 demonstrates an example of activity-based DSM application, the matrix of activities and information flows. By rearranging the rows and columns, the amount of feedbacks is reduced, as the empty squares above the diagonal show. This reordering is called block diagonalization of the matrix, and it reveals improved activity sequences. These larger blocks along the diagonal essentially represent the critical path of work duration. The nodes shown in Fig. 4.5 represent logical places along the critical path to locate "toll gates", i.e., opportunities for a project review. The optimization approach to an activity-based DSM implies that the right information is available at the right place at the right time and activities are properly sequenced.

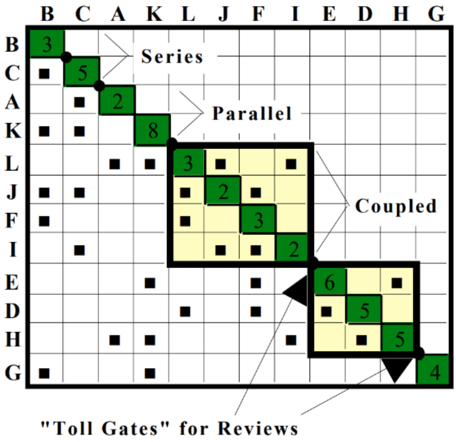


Figure 4.5. Partitioned activity-based DSM for a hypothetical process showing process sequence (Browning, 1998)

In the parameter-based DSM application (see Fig. 4.3), the modelling of the design process takes place in a top-down fashion and coincides with the essence of the vertical causality law in systems engineering. The method for building and analysing a parameter-based DSM is similar to that used for an activity-based DSM. An additional goal could be to minimize what Krishnan (Krishnan et al., 1997) has called design "quality loss", i.e., the over-constraining of downstream options by upstream decisions.

In summary, all four types of DSMs discussed in this part demonstrate the strength of matrix-based approaches: concise visual representation of complex relationships. Without any doubt, it is a very useful basis of synergy-based thinking.

Let us now examine mathematical tools to support the proposed design platform. The mathematical theory of matrixes founded between the 19th and the 20th century made substantial progress during the last century. Numerous publications in the field of DSM technology starting from Steward are available (Kusiak&Wang, 1993; Gulati&Eppinger, 1996; Baldwin&Clark, 1998; Browning, 1998; Malmström, 1998; Malmqvist, 2001; Eppinger, 2004).

All mathematical support to use the DSM technology created in the Massachusetts Institute of Technology is available for open use (Eppinger&Browning, 2012). For timing the use of advanced simulation techniques, such as the Latin Hypercube Sampling (LHS) and parallel discrete event simulation (Cho, 2001), are also openly available.

The DSM method can be used for structuring the information flows among tasks and capturing the iteration loops. This allows computing the probability distribution of lead-time in a resource-constrained project network where iterations take place among sequential, parallel and overlapped tasks. In each simulation run, the expected durations of tasks are initially sampled using the LHS method (Keefer&Verdini, 1993; Browning, 1998; Cho, 2001). A special feature of the LHS simulation model is the use of triangular probability distribution (see Fig. 4.6) to represent the characteristic of task duration since it offers comprehensibility to a project planner (Williams, 1992). It has been found that assessing the 10th and 90th percentiles of the expected duration is more reliable than the extremes of the Probability Density Function (PDF), which are typically outside the realm of experience (Keefer&Verdini, 1993). The model uses the Latin Hypercube Sampling (LHS) method to incorporate the uncertainty of the expected duration of a task based on three estimated durations: optimistic, most likely and pessimistic (McKay et al., 1979; Scheaffer&McClave, 1986; Wyss&Jorgensen, 1998). After calculating the extreme values of the PDF, it divides the range between them into N strata of equal marginal probability $1/N$, where N is the number of random values for the expected duration. Then, it randomly samples once from each stratum and sequences the sampled values randomly. Figure 4.6 illustrates the LHS procedure.

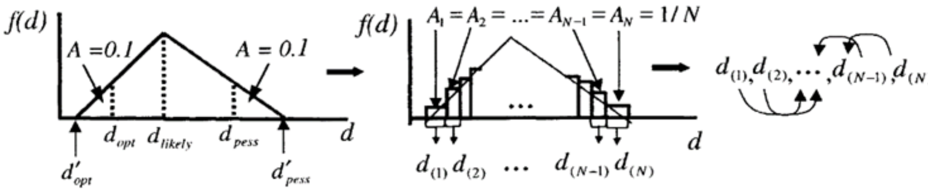


Figure 4.6. Latin Hypercube Sampling (Cho, 2001)

The DSM analytical model allows for describing the complex behaviour during the development processes having overlapped tasks and sequential iterations. In addition, it is possible to distinguish three types of information flows in a task information flow - at the beginning or at the end of the task, and also in the middle (see Fig. 4.7).

(a) First Type

(b) Second Type

Figure 4.7. Overlap amount and impact between tasks (Cho, 2001)

A very complicated problem here is the formalization of iterations. Eppinger defined an iteration as the repetition of tasks to improve an evolving development process (Eppinger et al., 1997). However, iteration may be referred to as rework caused by other tasks without including repetitive work within a single task. The model assumes that the planned rework of a task is generated due to the following causes (Smith&Eppinger, 1997; Browning&Eppinger, 2000; Ballard, 2001):

- Receiving new information from overlapped tasks after starting to work with preliminary inputs;
- Probabilistic change of inputs when other tasks are reworked;
- Probabilistic failure to meet the established criteria.

In the proposed model, the first cause gives rise to overlapping iterations and the second and the third give rise to sequential iterations. Parallel iteration of a limited number of tasks is simulated in this model by combining overlapping and sequential iterations. Overlapping has been described as a “core technique for saving development time” (Smith&Reinertsen, 1995).

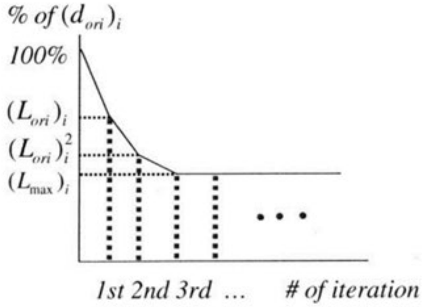


Figure 4.8. Learning Curve (Cho, 2001)

The rework model assumes that the learning curve decreases by $(L_{ori})_i$ percent in each repetition (see Fig. 4.8). Thus, rework amount is calculated as the original duration multiplied by the rework impact of a learning curve.

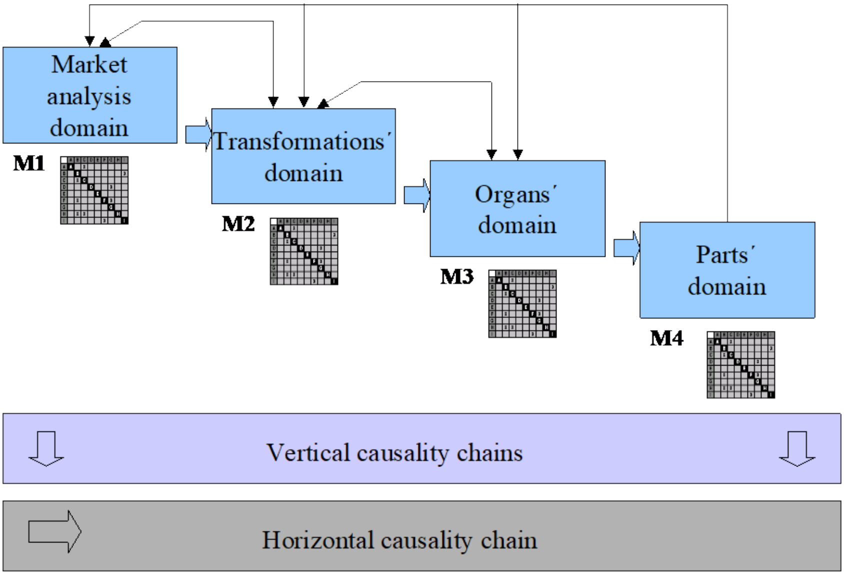


Figure 4.9. The integrated platform for interdisciplinary system design (Kaljas, 2005)

Integration of the Theory of Design Domains (TDD) and the Design (or Dependency) Structure Matrixes (DEM) technology enables us to create a good design platform for involving marketing conditions, timing and human competence dimensions in a synergy-based manner (Kaljas&Reedik, 2005). Fig. 4.9 presents the essence of the proposed generic platform for interdisciplinary product and system design. 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 to guarantee that the developed products be competitive on the market. Matrix 2 of the transformation domain is the parameter-based DSM that gives an algorithm for the design process and opens a possibility to reach the optimal synergy level and performance of the system designed. Matrix 3 in the organ domain represents parametrical activities in the selection of suitable active elements or organs and their mode of action for interdisciplinary artefacts that create suitable performance effects. Matrix 4 of 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 performance tasks are solved and its total behaviour assured.

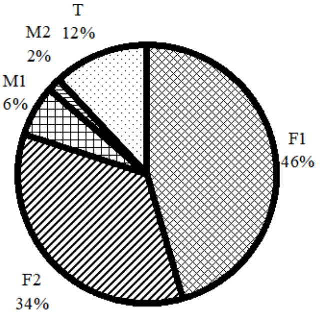
In summary, it is necessary to underline the flexibility and suitability of the described approach for achieving synergy-based priorities. It makes it possible to realize the negative synergy filtration principle and to reach the optimal positive synergy level set by the market during minimal time. But a full exploitation of the possibilities of the proposed approach needs an experienced professional team and pays back at complicated system design.

4.3. Human aspects of equipment control system design teamwork

To enlarge the scope of the study of human shortcomings in the teamwork described above in section 3.2, the focus of that research was shifted to the development of equipment control system. This database was completed by joint efforts of company branches in the Nordic countries. As compared with previous mechatronic product design and production database, pneumatic and hydraulic components were added. For the analysis based on real experience gained from automation system design and application, a unique database of human and technical shortcomings was compiled, comprising more than 13,000 equipment control system design and launch information (Kaljas et al., 2004a). It is at the same time a very sensitive domain and so for understandable reasons, the companies involved are anonymous.

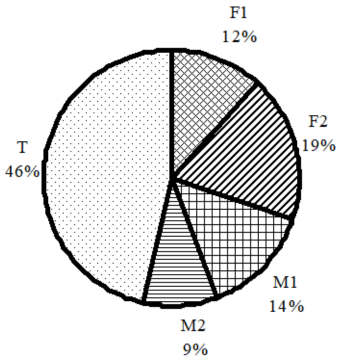
The classification principles of the human shortcomings are the same as shown above in Fig. 3.6. It should be added here that in a complete analysis, another detailed classification level was on trial run, but it does not prove the ability to carry over additional substantial information for the synergy-based approach. In equipment control systems, cooperation between the customer and the system application team is so closely intertwined that only an analysis of summarized shortcomings is possible here. Even in those conditions, quite an interesting difference between well-established "old" and comparatively "new" technologies can be observed.

Fig. 4.10 shows the statistical analysis of human shortcomings for equipment control system design and application for such a well-established area as electro-pneumatics/hydraulics systems with programmable logic controllers on the top of hierarchy. At first sight, the dominating share of faults is conspicuous. In category 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.



For categories of faults and mistakes see Figure 3.6

Figure 4.10. Human shortcomings at integrating of "old" technologies (Kaljas, 2005)



For categories of faults and mistakes see Figure 3.6

Figure 4.11. Human shortcomings at integrating "new" technologies (Kaljas, 2005)

Fig. 4.11 presents the analysis of shortcomings for equipment control systems where a comparatively new technology - servo drive control is used. On the same balance of faults F1/F2, the dominating share of technical problems T can be noticed. The reason seems to be that the new components are also still in the infant mortality development period.

Now a more detailed description of the mistakes will be given as they are almost common for both levels of technology development. Typical mistakes in the category of M1 are caused by the lack of team's core competence. As an example, when applying the positioning system, it may happen that the proposed 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 in the conditions of high dynamics. Most of the mistakes of category M2 occur when it appears possible to establish or to tune the controlled process parameters only during a later experimental study. The dominating share of 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; however, it appears later on the market that its parameters are on a level lower than declared.

A survey of engineers and managers in the automation field has shown that these extra costs of removal of shortcomings can attain up to 5-10% of the system's cost, which in reality is quite an impressive loss. All the results of the negative synergy study described above are somewhat alarming, as misunderstandings and negligence are forming up to half of all shortcomings that can be easily avoided.

The most important problem here is how to improve synergy in teamwork to avoid faults of the category of F1 based on mutual communication. Today's information technology is offering improved online communication possibilities also for dispersed teams and in some time, the share of that type of faults has to decrease. It is absolutely necessary to run a dated database to grant that all changes made in the system 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. In terms of mistakes M1, most of the problems are caused by lack of competence and therefore special attention must be paid to the continuous upgrading of the personnel. Newcomers in the automation area are recommended to rely on the consulting service in the beginning. 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 current design and during the start-up of the systems, new unknown matters may occur.

4.4. Case study for the development of an accurate positioning system

To provide a deeper insight into the proposed methodology, it is probably reasonable to start with a case study. The goal of stepping up the synergy level of allied technologies is to reach the market-driven performance level with minimal possible expenses on product development and production (Kaljas, 2005). It is appropriate to demonstrate the practical realization of these guidelines on the basis of a real case study, which was initiated to improve the accuracy of a failed pneumatic positioning system (see Fig. 4.12).

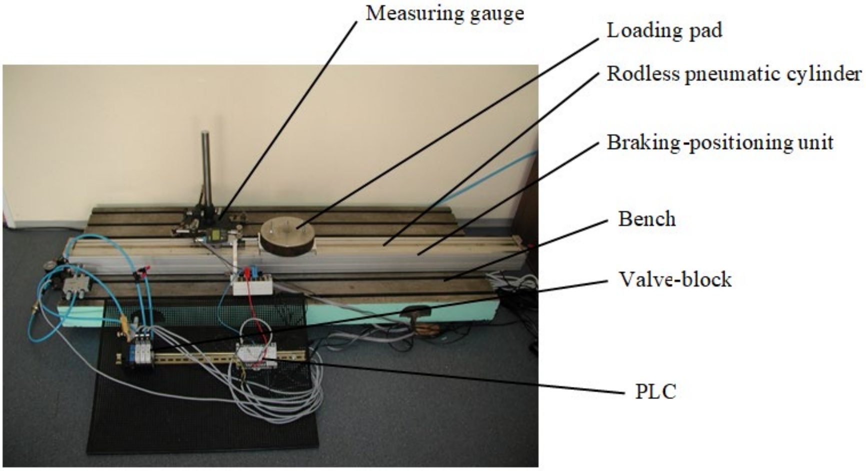


Figure 4.12. Experimental stand of a positioning system (Kaljas, 2005)

The dependence of the initial positioning accuracy on the positioning speed was determined experimentally and the results are shown in Fig. 4.13. This positioning accuracy (repeatability) contains the dispersion of the switching time of the controller and the pneumatic control valve as well as 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. However, because of low level accuracy of this positioning device as well as low competitive level, the producing company stopped this development.

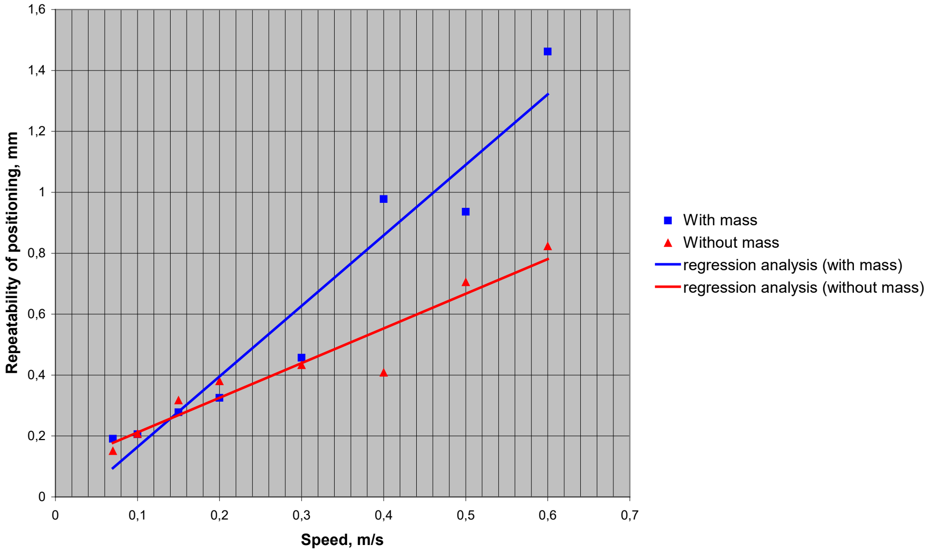
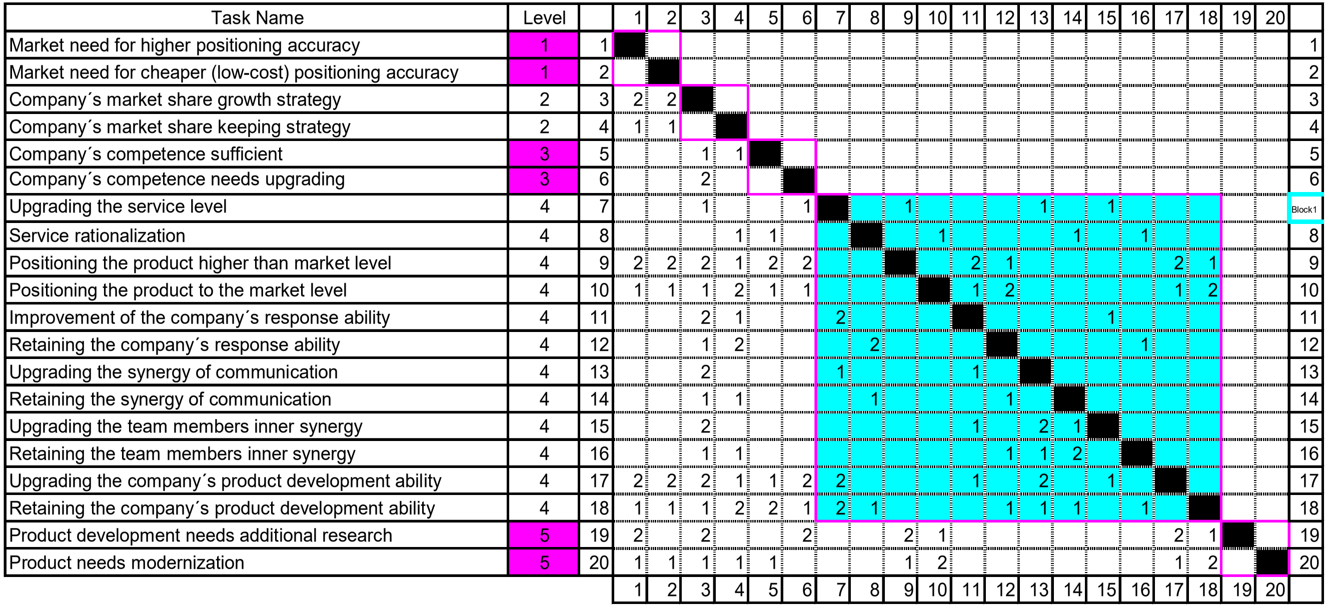


Figure 4.13. Initial positioning repeatability of a pneumatic positioning system (Kaljas, 2005)

From the point of view of design activities, this case certainly falls under the category of past design or modernization. Therefore, as compared with the design of a new product, design activities are not required in their full content. Thus, in the framework of the study, only two matrixes are needed: the activity-based DSM for the market analysis domain and the parameter-based DSM for the integrated transformation and organ domain. To evaluate the influence of the human shortcomings described in section 4.3, the unique database data were included.

For the market analysis domain (see Fig.4.14), the DSM for 20 inputs was compiled, characterizing trends in the market environment, the product strategy of the company and its personnel competence in the 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. So in that situation the automation market in the Nordic countries was supposed to be decreasing. All the interactions in the 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 the product or system performance. Column numbering in the table is the same as for horizontal rows.

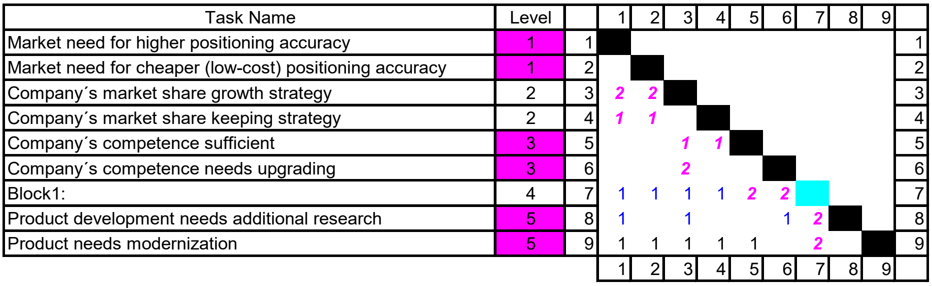
The activity-based matrix for the analysis of the market shown in Fig. 4.14 is already allocated to scheduling transformation. In this transformation process, activities are arranged with a goal to move all the interactions under the diagonal, which gives the possibility to use the information of previously 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 in the best possible way. The general goal of compiling this matrix is to work out the company's survival policy for the period of decline in the industry. All the activities are also grouped on the consecutive levels, which mark the decision-making steps. In the present case, on the first level, it is necessary to provide the market analysis. The two next levels form an invisible block of traditional 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 be made about product modernization and research help from universities. This is a simple demonstration case and you may say that it is a normal way of scheduling of activities, which is possible also without any DSM. However, commonly, design tasks are more complicated, moving out from the brain seizure.



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 4.14. Activity-based DSM for market analysis after partitioning (Kaljas, 2005)

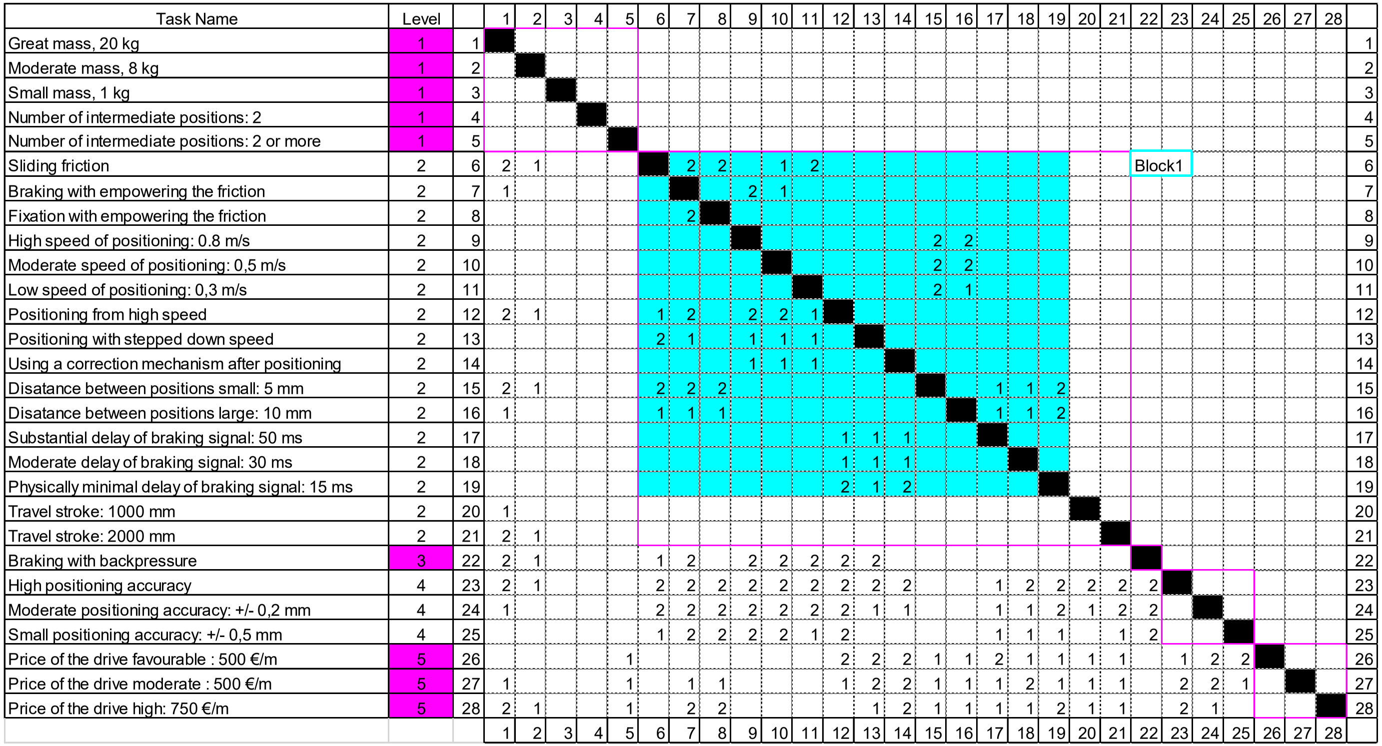
Here it is also necessary to pay attention to the fact that process scheduling is the only first step of the process and the still visible information about the synergy of interactions is so far only partly used. After the collapse of the blocks in the matrix, the analysis reaches timing problems of the activities (see Fig. 4.15). Here we can distinguish the critical bindings (numbers in italics) in the iteration context of the information transfer and prognosticate the probabilistic duration of the whole process, providing all the activities in an optimistic, likely or pessimistic evaluation of duration, taking into account the learning time (Cho&Eppinger, 2001). But here it is necessary to remind the main goal of the present study - 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 due to strongly intertwined inputs for a process, scheduling is difficult, whereas market analysis is one of these situations. Therefore it is appropriate to concentrate only on strong interactions, as a dissipating use of interactions may lead to the situation where partitioning becomes impossible. But in any case, a trustworthy roadmap for a development process is created with a possibility of keeping a comprehensive overview of the decision-making process.



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 4.15. Timing analysis of the process (Kaljas, 2005)

The next step in the design activity is to draw up the parameter-based DSM for the allied domains of transactions and organs. Such joining together the domains distinguished above at the modernization of the system is very common. Initially, 40 inputs were nominated from which after careful selection, 28 were selected for the final matrix. The same procedure of the evaluation of synergy-based interactions on 2-1-0 scale was provided. Figure 4.16 presents the parameter-based DSM after partitioning. The expected outcome of this analysis is a proposal that the structure of a more exact pneumatic positioning device at a moderate price increase is real. As the figure shows, five levels of decision-making are distinguished.



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
Travel 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 4.16. Parameter-based DSM after partitioning (Kaljas, 2005)

The first level contains an invisible block of the initial parameters having no interactions. The second block is a real design matrix where all the important design parameters supporting the performance of the product are presented. The next 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 the problems that could not be solved earlier.

Let us concentrate on the central block where the key of the expected solution is hidden. 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 than that attained by the use of expensive servo systems. The increasing friction in combination with the backpressure in the cylinder in the present prototype seems to be a good solution but it does not give the expected accuracy as 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 be built on the basis of roller slide ways and with the control servo of optimal speed having a separate braking system. However, altogether 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 built and experimentally tested (see Fig. 4.17) and the testing results are shown in Fig. 4.18.

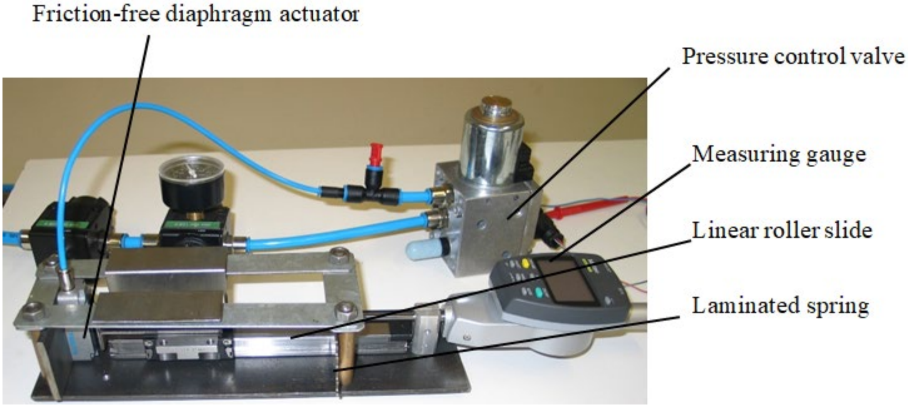


Figure 4.17. Testing of the model of the correction device (Kaljas, 2005)

We can see that the accuracy of the redesigned model is much higher than the market expectations need. The correction function is close to linear and the accuracy (repeatability) of the system is about ± 0.0045 mm, which is competitive with the accuracy of the measuring system; moreover, it is far more accurate in view of market expectations. The estimated price of the system is 40-50% higher than that of the failed prototype. Thus, a situation is reached where cooperation capabilities of the system elements are used in a synergy-based manner on the optimal level, satisfying price limits on the market.

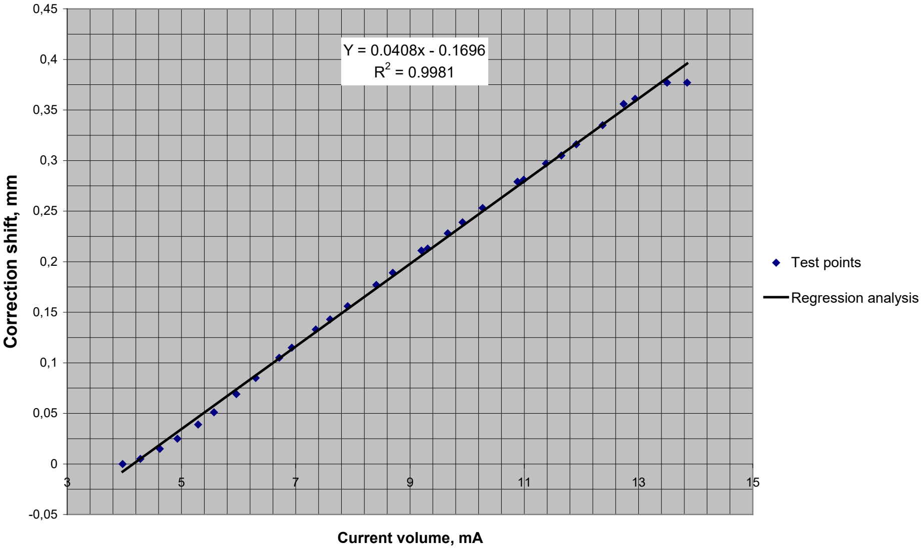


Figure 4.18. Final positioning accuracy of a pneumatic positioning system (Kaljas, 2005)

4.5. Adaptive methodology for synergy-based design

In the following, we will evaluate the efforts made towards objectives concerning the features of the new design methodology set up in the previous section of this chapter. The reader can observe the perspective to bring such characteristics as design parameters, market conditions, human factors, and reliability problems under one umbrella. This allows making up for mutual weaknesses or negative synergy and amplification of useful effects or positive synergy between the allied technologies. The perspective to keep the design parameters and components, design team cooperation, and market situation visible during the whole design process is of substantial importance.

Obviously, with respect to the integrated platform for interdisciplinary system design (see Fig. 4.9), the proposed methodology integrates all the listed sides of the design process starting from market conditions, design parameters and human factors into one framework. The synergy-based thinking as the binding agent for integration is also successfully applied. At the same time, the synergy concept of the co-work on all integrated technologies and human teamwork levels is enraptured. The DSM technology enables keeping continuously an eye on all these complicated interactions during the whole design process. So it seems that in general the estimated goals are achieved.

The main problem here is how the synergy characteristics are integrated into the framework of the design methodology. The DSM technology makes it possible to involve the description of all interactions between system characteristics in a synergy-based manner. 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. Transformation of the DSM matrixes provides for solving product architecture problems and finding out an optimal process scheduling. At the same time, the processing of the matrixes can be built up on saving its synergy base. In summary, we can suggest that synergy is the universal criterion for the evaluation of technical, marketing and human behaviour aspects in the design process. The basic idea of synergy allocation is the development of a new design methodology of interdisciplinary systems as filtering systems that have a capability of allowing through and amplifying engenders of positive synergy and impeding the entrance of the negative synergy effects.

In the context of the increase in synergy aspects, it is reasonable to start from positive synergy allocation. All innovations on the technical side of integrated technologies are the natural source of positive synergy. It is also clear that compensation of the weaknesses or negative synergy is also a basis of movement in the direction of positive synergy. Positive synergy cannot be expressed as a sole universal parameter of the designed system, but rather as a set of parameters related to functionality, operation speed, productivity, energy consumption, weight, start-up time, and service dependability. In the transaction domain (see Fig. 4.16), integration starts from physical processes and continues through other domains. The maximum value of positive synergy means reaching the situation 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. It is obvious that raising the synergy level needs remarkable resources. It is widely known that the development cost for safety critical systems such as space, military and nuclear technology is about 10 times higher than that of non-safety critical consumer products of the same purpose.

Generic foundation of positive synergy is optimization in its wider interpretation. 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 reality, all of these three approaches complement each other, calling forth total synergy of performance. In complicated situations, outside the brain's seizure, we have to apply mathematical tools. What about positive synergy on the human side? It is clear that success in the teamwork strongly depends on the synergy in thinking and the actions of the team members. The overall principle here is to guarantee the working conditions to foster creativity and effective teamwork.

In any case, it is not possible to ignore negative synergy facts due to their insidious action and a tendency to re-occur. The technical side of negative synergy is closely related to the reliability characteristics (see section 3.1.2). In the synergy context, reliability can be treated as a process where the synergy of the operation of the components is gradually reducing (wear, emission, etc.) or it is caused by chain failures between allied technologies. The synergy-based design methodology has many possibilities for pressing down the influence of the technical side of negative synergy. Another important key for reducing the influence of negative synergy is to increase the team's core competence and increase the synergy of teamwork during the design process.

For every design methodology, it is important to have a possibility to prognosis the development time, including the human shortcomings or negative synergy effects. The best solution seems to be the use of Monte Carlo statistical modelling with Latin Hypercube sampling (see section 4.2), which opens a possibility for probability-based simulation of the sequence of mutually dependent processes used in the DSM technology (Cho, 2001). It enables also planning the timing of the complicated probability evaluation processes containing iterations, rework and learning and therefore avoiding superfluous over- or underestimation at resource planning (Fodor&Kacprzyk, 2009).

When accepting any new methodology, the results of its testing in practice are most important. The proposed synergy-based approach was first applied for the redesign of a failed pneumatic positioning system (see section 4.4). The validity of the proposed design methodology has been proved experimentally and the modernized design has demonstrated its increased accuracy at the competitive market price.

Finally, we want to find out where the synergy-based approach would stand among existing engineering design methodologies. The question is if the approach is prescriptive, descriptive or something between them or just a new one. The proposed way for synthesizing a design team's own roadmap algorithm to move ahead in the design process was successfully tested on the real pneumatic positioning system. It was complicated and time-consuming to compose useful and suitable DSM matrixes, which may be a great challenge to a design team. Here simultaneous professional knowledge of product architecture, product development process, and organizational work is required; success in the use of the proposed design model depends on the existence of these qualifications. At the exploitation of the proposed methodology, the professional team is supported by the automatic synthesis of the optimal design process algorithm that leads to improved product performance at the shortest design time. Low competence of the design team leads to imperfect DSM where some important interactions may be absent or incorrectly evaluated. So it is possible to allege that a **new family of adaptive design tools** has been developed based on adaptability to the level of competence and expert knowledge of the design team.

5. QUALITY ASSURANCE – A SYNERGY-BASED APPROACH

T. Hindreus, V. Reedik

5.1. Overview of quality management systems development

The word *quality* originates from the Latin word *quālitās* and from time immemorial it has been used simultaneously with its direct notion for the evaluation of characteristics, value, goodness, etc. In the modern society, the use of the concept of quality is still under remarkable evolvement; today we talk in a self-evident manner about the quality of life, emotions, environment, education, service, etc. In the present book, the area of interest is delimited to the concept of product development and its quality assurance. The main difficulties that arise while defining the quality of the product are associated with the notion that it is a technical, perceptual as well as a market-driven concept.

Quality thinking has surrounded humanity from the beginning of times. Primeval humans carefully followed the performance quality of their arms and they also ornamented their possessions, which shows that perceptual quality was important for them too. Probably the first attempt to measure quality was made in ancient Egypt where the priests measured the overflow level of the river Nile with a special pole. As a result, they estimated the quantity of the settled mud and the taxes were adjusted according to these results. In ancient Babylon, King Hammurabi was the first to officially proclaim the law on human actions quality (King, 2005).

In the early 1900s, F. W. Taylor and H. Ford recognized the limitations of the methods being used in mass production at that time and the subsequent varying quality of output. Taylor established Quality Departments to oversee the quality of production and rectifying of errors (Taylor, 1911). Ford emphasized standardization of design and its components to ensure that a standard product was produced (Ford&Crowther, 1922). At that time, management of quality was the responsibility of the Quality Departments and was implemented by inspection of product output to "catch" defects. Application of statistical control came later as a result of the development of World War II production methods. The first quality management principles are the outgrowth of work done by W. E. Deming. He declared his 14 Points for Management (Deming, 1986) in order to help people understand and implement the necessity of quality thinking.

The technical side of the product quality continues to be a key driver of the product development process and more attention was paid to improving the upstream activities of the product development process to ensure that quality is built in the product from the very beginning (Feigenbaum, 1952; Goldratt& Cox, 1984). Probably the most comprehensive analysis of how quality should be designed into products is comprised in the concepts of Design for Quality (DFQ) (Mørup, 1993) and Quality Function Deployment (QFD) (Akao, 1994). The quality paradigm has been also widening on the customer side and dealing with "perception", "value", "feeling" and "mind-set" has become a modern field of research. Concepts such as globalization, mass customization, product branding, and e-commerce suggest that product quality paradigm is still under evolvement (Cook et al., 1997; Robotham&Guldbrandsen, 2000). Historically, there exist innumerable concepts and systems for improving the quality of business, which form a common notion called quality management systems.

During World War II, there were quality problems in the British military industries such as ammunition industry, where bombs were exploding in factories during assembly. The adopted solution was the requirement set to factories to document their manufacturing procedures and to prove by record-keeping that the procedures were being followed. The name of the standard was BS 5750, and it was known as a management standard because it did not specify what to manufacture, but rather how the manufacturing process was to be managed. In 1987, International Organization for Standardization adopted BS 5750 as an international standard ISO 9000 (ISO 9000:2000; Seddon, 2000a,). ISO 9000 is a family of standards for quality management systems, which are continuously complemented.

To achieve excellence, companies need a corporate culture of treating people as their most important asset and provide consistent efforts to attain high quality products and services. Such environment has supported the wide acceptance of Total Quality Management principles that emerged as a new, challenging and marketable philosophy (Juran, 1988; Oakland, 1989). There is a strong belief among the managers that Total Quality Management (TQM) and ISO 9000 standard series take good care of quality and quality certification of companies and grant their trustworthiness in quality assurance (Seddon, 2000b).

Now let us move to issues related to the real effectiveness of quality certification. It is necessary to underline that proper quality management improves business, often having a positive effect on investment, market share, sales growth, sales margins, competitive advantage, and avoidance of litigation (Dalgleish, 2005; Barnes, 2000; Inaki et al., 2002). According to the Providence Business News (Providence Business News, 2000), implementing ISO standards often gives the following advantages: creates a more efficient operation, increases customer satisfaction and retention, enhances marketing, improves employee motivation, promotes international trade, increases profit, reduces waste, and increases productivity. Many different techniques and concepts have been evolved to improve product, production and service quality, including Statistical Process Control (SPC), Quality Function Deployment (QFD), Hoshin Kanri, Zero Defects, Theory of Constraints (TOC), Six Sigma, Kaizen, Total Quality Management (TQM), and Balanced Scorecard (Kaplan&Norton,1992).

In summary, the picture described above is multi-coloured and it is difficult to differentiate between the borders of the intertwined approaches.

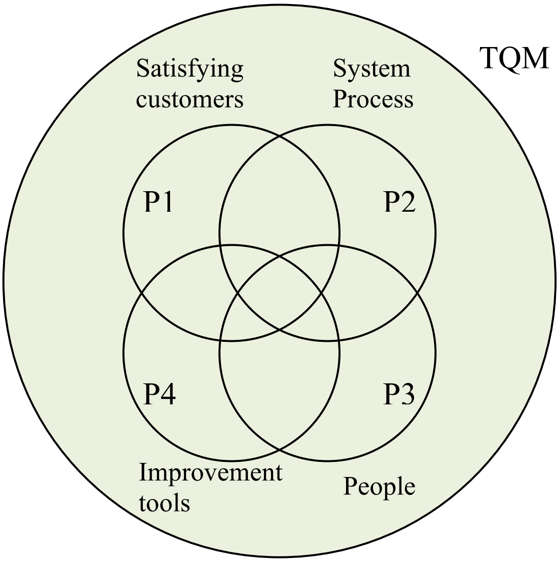


Figure 5.1. The four pillars of TQM (Ho, 1999)

However, in this multiplicity, it seems that TQM, which emerged as a new, challenging and marketable philosophy, is the most suitable basis for the development of an integrated synergy-based quality assurance system. It involves the first three spheres of changes in an organization - people, technology and structure (Oakland, 1989). Ho proposed the 4-pillar model (see Fig. 5.1), which brings customer's requirements into the system (Ho, 1999). The additional pillar “satisfying customers” is vital because it explicitly addresses customer’s requirements and without it, TQM would have no objective. TQM should be understood as management of the system through systems thinking, which means understanding all the elements in the company and putting them to work together towards the common goal (ISO 9001:2000; Singhal, 2003). In reality, the focus should be especially on the product’s performance quality to ensure that the product satisfies the customer. It seems that this philosophy is a suitable partner for the synergy-based thinking.

The most competitive of the quality assurance tools for synergy-based integration are the different developments of Design for Quality (QFD) systems and the Kaizen approach. The four-phase QFD approach is focused on product design and is based on the analysis of parametrical matrixes in order to translate customer needs to technical characteristics with the following matrixes for process planning and quality control (Mørup, 1993). It is a time- and stage-dependent system without a visible deeper integrating basis, but it suffers mainly from the lack of an integrating meta-tool. The Kaizen philosophy (Imai, 1986) is probably the closest to the synergy-based approach as it is based on human development as a source of continuous improvement. The provided analysis shows that the synergy-based approach seems to be a suitable universal meta-tool for the closer integration of product quality and quality management systems.

5.2. Quality and synergy – similarities and differences

In the discussions described above, the terms quality and synergy have been so intertwined that we should find their mutual relations. Integration of synergy-based engineering design methodology and quality management philosophy to a united system seems to be very attractive and is a springboard for our further debate. The main difficulty here is probably the seemingly unmatchable character of synergy and quality as well as difficulties in their quantitative evaluation.

It seems that in the most progressive viewpoint, the quality is defined mostly by the customer or end user and it is based upon that person's evaluation of his or her entire customer's experience. For example, any time you buy a product, you form an impression based on how it was sold, how it was delivered, how it performed, how well it was supported. It is obvious that the described approach is valid only for non-safety-critical consumer products.

In terms of synergy, it is necessary to point out some difficulties when positive and negative synergy are concerned. There is "something" that makes integration of technologies successful and it is usually called "positive" synergy. However, sometimes we witness an unfortunate integration of allied technologies unsuitable to accomplish the planned task. For symmetry, it is appropriate to call it a "negative" synergy. Linguistically, the opposite of positive synergy is asynergy. However, in the present context, it is purposeful to stress the dynamics and direction of the effects of synergy-based optimization and therefore the pair positive/negative synergy is most appropriate.

Successful teamwork is the main source of positive synergy. In terms of negative synergy, human shortcomings play a leading role, as it is impossible to imagine that any technical artefact (before the robot-age) is able to come into being without human involvement. Human faults and mistakes in marketing, design, production due to incompetence and miscommunication are the core basis for growing negative synergy and are reasons for ”bad engineering”.

Returning to the interrelations of synergy and quality, it seems that the goals and nature of their assurance are quite close to each other; all that is made to increase synergy promotes better quality and vice versa. It seems that quality is more customers addressed and enterprise networking parameter and synergy is a driving goal in the systems integration. As a result, we can conclude that in any case, synergy and quality levels have an optimal value determined by the competitiveness of the systems on the market (Hindreus&Reedik, 2002).

The investigation of the reasons of "bad engineering" with a focus on its technical and human aspects has shown the dominating role of human faults and mistakes. It is obvious that TQM is based fully on human activities and the technical side is marginal. Without any doubt, science and engineering are creative professions where discovering new patterns in technologies and creation of novel solutions are based on professionalism. At the same time, the ability to use this individual level of competence depends a lot on synergy in the functioning of the whole human organism. The old saying "Mens sana in corpore sano" contains the main rule how to reach a better synergy in personal activities. Experience has shown that the maximal productivity in our professional work is far from stability. When our organism is tired, we start to make faults due to negligence. In extreme situations: in stressful situations and under the influence of alcohol, the human being can easily lose all the positive synergy in behaviour and faults occur in communication; thus, the effects of negative synergy can easily dominate. So naturally, human behaviour depends much on his/her inner synergy. In human behaviour in teamwork, it is appropriate to start from the well-known example of synergy allocation in sporting games. For the team to perform well, it is important that the team members know each other's weaknesses and strengths. So, the secret of a successful game is that while playing, every member must find the best strategy to realize synergy between the capabilities of the members.

To summarize the discussion of the relations between synergy and quality, an attempt has been made to compile and analyse the quality-synergy relations by the matrix view in the context of the interdisciplinary system design (Hindreus&Reedik, 2003). The matrix was built up according to the DSM technology rules that have 20 indicators of quality and synergy. The indicators are formed into equal groups, representing the classical pillars of the TQM system and pure synergy category. Such a classification cannot be complete, as some indicators are also intertwined with indicators from other groups. The correlation steps were marked as follows: strong, medium and weak. As a result, the proposed quality and synergy correlation is quite impressive: on the medium level - 67% and 10% on the strong level. This is an encouraging basis to the further use of the synergy-based thinking as the meta-tool for integration of product development and quality assurance systems.

5.3. Human aspects at quality systems certification

F. W. Taylor was one of the first to attempt to analyse human behaviour at work systematically (Taylor, 1911). He applied the principles of machines turning individuals into the equivalent of machine parts to complex organizations. Just as machine parts were easily interchangeable, cheap and passive, so should human parts be in the machine-model of organizations. Surprisingly, the core elements of Taylor's scientific management theory remain popular today but they have naturally been modified and updated. Critics of Taylorism were calling attention to the "seamy side of progress," which included severe labour/management conflict, apathy, boredom, and wasted human resources. These concerns led a number of researchers to examine the discrepancy between how an organization was supposed to work versus how the workers actually behaved.

The most famous of these studies was conducted in the Hawthorne Western Electric Works (Mayo, 1949), which showed how work groups provide mutual support and effective resistance to management schemes to increase output. Conducted in the 1920s, these studies started as a straightforward attempt to determine the relationship between work environment and productivity. Resulting from the research, the researchers found that they were dealing with socio-psychological factors that were not explained by the classical theory, which emphasizes the formal organization and formal leadership. Hawthorne's studies helped us to see that an organization is more than a formal arrangement of functions; it is also a social system. Later in the last century, research into human behaviour was focused more on the psychology of work.

There are still some dispersed data available about the quantified influence of human shortcomings in engineering and management activities (see section 3.2). The experience has shown that human shortcomings in different domains of engineering activities are different and therefore it is necessary to conduct a separate study of the quality certification process.

A 10-year database of human shortcomings was compiled where the results of quality management certification processes of more than 200 production companies were analysed (Hindreus, 2009). The certification process itself is the procedure where the third part, an independent inspection body, gives written evidence that the product, process or service corresponds to the requirements of ISO guidelines. In practice, this means that auditors from an accredited certification body visit the company that requires certification and perform the audit of its quality management system. Technically, the research is based on scoring the human shortcomings documented in the certification process with their further classification and statistical evaluation. In average, the number of observations to discuss is approximately 20-30 per company (Hindreus&Reedik, 2006a).

After collecting all shortcomings, these were classified into faults and mistakes according to the classification scheme. For the classification of human shortcomings and for keeping the possibility of comparative analysis, we use the earlier scheme shown in Fig. 3.6. Only the nature of the signs needs to be specified. The study presents the following three phases of TQM: product development preparation (PDP), product design and resources management (PDRM), and product realization and analysis (PRA).

Fig. 5.2 presents the results of the statistical analysis of human shortcomings in the quality certification area. For better comparison, the integrated columns are used with connecting lines that have no physical content. During the phase of product development preparation (line PDP), the typical faults **F1** are as follows: the responsibilities inside the organization are not fully defined; the path and procedure of documentation confirmation are not legitimated clearly; overviews of clients' requirements are absent, etc. Faults **F2** – valid instructions are not used; the introduce procedures are not followed; there is anarchy in the drawings system, etc. Mistakes **M1** – inadequate knowledge of legal acts, as a result of which the requirements set up are insufficient and, therefore, cannot be followed. Mistakes **M2** are based on lack of future perspectives when the current procedures are out-dated and better solutions are available.

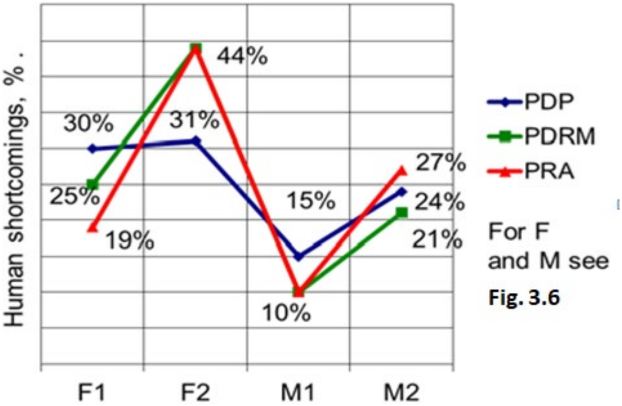


Figure 5.2. Human shortcomings in quality management (Hindreus, 2009)

The PDRM line in Fig. 5.2 shows the data of human shortcomings for the product design and resource management phase. The dominating deviations are: **F1** – professional instructions do not include qualification requirements, working environment does not correspond to standards, professional training plans are not followed; **F2** – personal development talks are not provided, professional knowledge cards are not filled in, safety regulations are not followed, warning signs are absent; **M1** – misleading warning signs, incompetence in storekeeping; **M2** – existing attestation systems are not used but at the same time, new ones have been introduced.

The PRA line in Fig. 5.2 presents an overview of human shortcomings in the product realization and its analysis phase. The typical deviations are: **F1** – the timing of measuring equipment verification is not established and the real situation is out of control, the client's requirements are not followed; **F2** – safety regulations are not followed, internal audits are missed, suppliers' evaluations are not provided; **M1** – in the procedures are made references to non-existent documents, conformity documentation is absent; **M2** – market research is absent, planning of future strategies is superficial, risk analysis is absent.

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

In the following, we will provide a comparative analysis of human shortcomings in different areas of engineering activities in the quality context. In Fig. 5.3, data on human shortcomings for different engineering design activities are compared. For a better comparison of the results, failures due to technical reasons are excluded.

In the first column QA, the results on human shortcomings of the certification of quality management systems are presented. The second column shows the results of human shortcomings in the design and production of a serial product – light fittings (LF) (Martin et al., 2006). The third column provides data on human shortcomings for the design and application of equipment control systems (EA) (Kaljas et al., 2004). The last column gives data on the design and commissioning process of factory automation systems (FA) (Kaljas et al., 2004b).

As we can see, the scope of databases covers the main areas of engineering design activities quite satisfactorily. It starts from the design of the interdisciplinary product, followed by the design and application of equipment control systems and complicated factory automation systems based on the computer systems. So it is a very comprehensive look at the reasons for "bad engineering" and finding ways to improve the quality of engineering work.

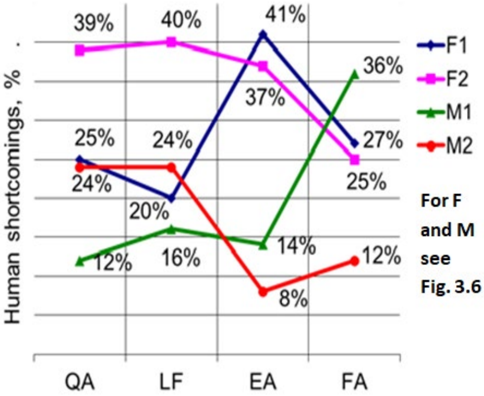


Figure 5.3. Comparative analysis of human shortcomings (Hindreus, 2009)

In the present mega-competitive world, the company's destiny is so strenuous and complicated and possibilities to survive so small that for a successful business, it is necessary to achieve maximal use of the capabilities of every team member. Well-organized teamwork is the key to better communication synergy where capabilities of team members at co-operation are used in the best possible way - compensating their weak sides and amplifying the common useful abilities. Only in teamwork, it is possible to press down most of human shortcomings, as accepted decisions are collective. Engineering team members are not equal in their competence and psychological capabilities. The inner communication synergy of individuals determines their fitness, creativity and in summary, their possible contribution ability to co-operation. It would be a real art to join different people to attain the maximum synergy in teamwork. However, it is the necessary precondition of both successful product development and quality assurance of all activities in the company.

5.4. Involvement of synergy dimension into the quality management system certification

In the 1990s when the companies entered the mega-competition age, the conflict between the growing demands for functionality and quality of products at a lower price became everyday reality. The continual renewing of a company's managing structure, work organization and product development tools were required to grant the sustainability of the company.

The basic idea of the present look at the integration of quality and synergy is to propose a novel approach to the integration of the still disunited assurance of product technical or performance quality and a company's quality management into one effective quality assurance framework (Hindreus, 2009). It is obvious that the concepts of quality management and product quality seem to be somewhat deported in the common quality assurance environment. For their closer integration, it is necessary to find a meta-tool of a higher level. The experience of renewal of interdisciplinary systems design methodology has shown that a suitable integrating meta-tool may be found in the synergy-based approach.

To integrate the product design quality and quality management systems, it is naturally preferable to use the same toolkit. According to the research described in section 5.3, quality management systems are based predominantly on human relations. It does not mean that it is possible to ignore technical shortcomings. Production quality depends also on the chosen production methods, the technical level of production equipment and tooling, skill of workers, etc. However, all these production conditions are created by engineers and so faults and mistakes are possible here too. As a result, in their essence, the above systems are quite close (Hindreus, 2001).

Certification of the quality management system needs a clear roadmap for realization of all prescribed activities scheduled to achieve the final solution at the shortest time. At the same time, the system's information and synergy relations between the activities must be visible during the whole certification time. The proposed methodology of certification must be also able to prognosis the probable duration of certification. The DSM technology enables us to present the relations between many optional entities in an understandable and visible way: human activities, technical parameters, different processes; after transformation of matrixes, they can be scheduled in an analysis algorithm. Also, the TDD approach can be suitable for organizing the structure of DSM matrixes of the quality management system in a time- and stage-dependent manner. To summarize, there seems to be no objections or restrictions to use the same synergy-based framework for the design of interdisciplinary products and to analyse the quality management system. At the same time, the integration of the product design quality and the concepts of the quality management system become real (Hindreus et al., 2006b).

A team-based DSM (see section 4.2) captures the information flowing between individuals, teams, and/or other types of groups within a program. Row entities will be referred to as teams. While a single matrix could perhaps show multiple organization levels, it is usually most helpful to ensure that the rows contain somewhat similar organization entities. Here the goal is to identify the key organization interfaces and to cluster teams into groups or meta-teams where interactions are most frequent (Browning, 1999). So the first evaluation given to the team-based DSM in the field of quality management seems to provide a case for further research.

It is important to underline that the goal of product development is not a new product but rather a successful business with this product. To attain a good business, it is necessary to integrate engineering design quality with other quality management activities in the company. The following debate is focused on quality-synergy relations in quality management activities (see Fig. 5.4). In the product development phase, the main attention is focused on the documentation review. It is the human nature that always fights against bureaucracy but in order to prove that the product development steps are taken correctly, they should be documented and verified. In building an effective quality management system, the involvement of top management is of utmost importance because only they should outline the company's quality strategy/policy. Finally, the timing of management reviews is of vital importance.

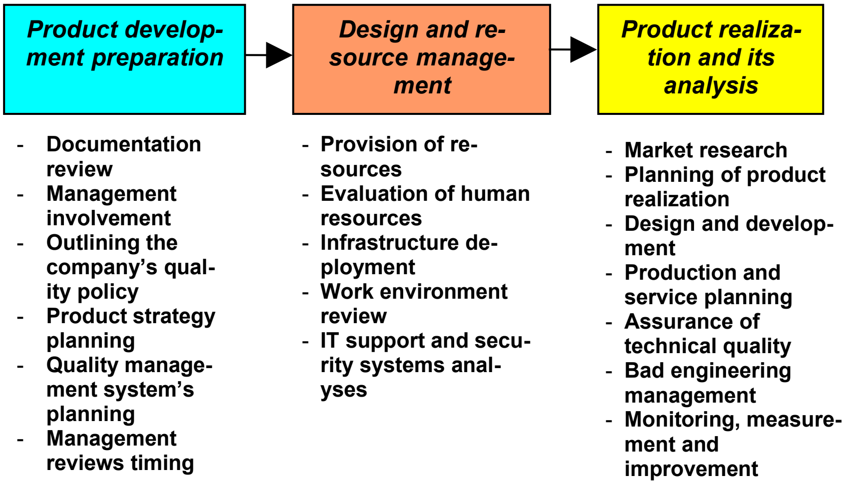


Figure 5.4. Deployment of quality management activities (ISO 9001, modified)

The design and resource management phase requires exact provision of resources, mainly evaluation of those on the human side, as it is the assets of the company that the results depend on. This requires also right deployment of the infrastructure, which includes the review of the work environment. Also, we should not forget about IT support and security systems analyses.

The final phase of quality management activities is product realization and its analysis. In this phase, human activities are related to product realization planning which includes market research, design and development, production and service planning, and also assurance of technical quality. All this is supported by monitoring, measurement and improvement. Human behaviour is involved in all the listed activities and the effectiveness of the quality management system depends fully on it.

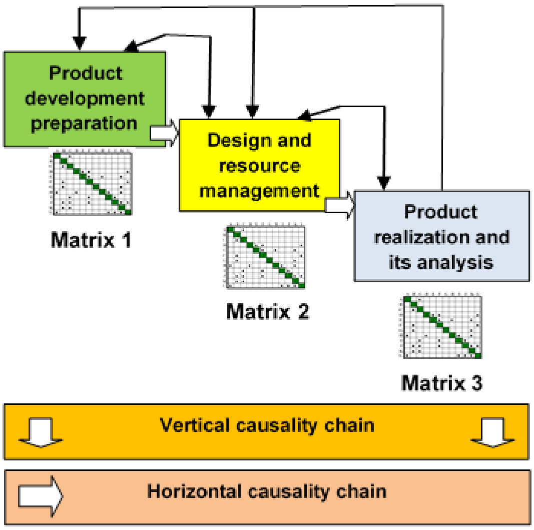
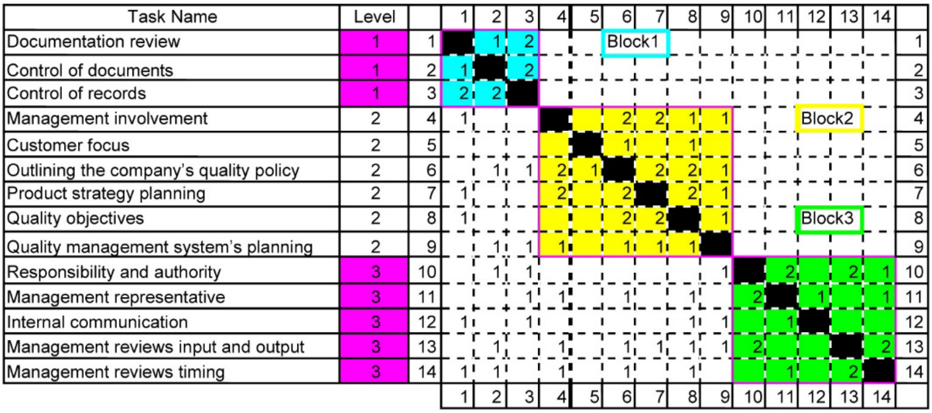


Figure 5.5. The integrated model of quality management (Hindreus, 2009)

By integrating (see Fig. 5.5) the technology of Design (Dependency) Structure Matrixes – DSM (Steward, 1981a; Eppinger, 1997) and the Theory of Design Domains – TDD (Hansen&Andreasen, 2002), it is possible to involve market conditions and human competence dimensions also in the quality management area. Basic knowledge about this integration is provided in section 4.2. In reality, for allocation of this synergy approach, it is necessary to compose three different matrixes, one for each quality management activity. Matrix 1 presents the activity type DSM that allows taking into account marketing trends and initiating synergy-based activities in product strategy and its planning to ensure that the developed products will be competitive on the market. Matrix 2 is the activity-based DSM that provides an algorithm for the synergy-based product development process and corresponding empowering of human resources, infrastructure and IT-support in the company. Matrix 3 is a mixed activity- and parameter-based DSM for the optimal planning of the product realization process and service in the framework of quality management.

Next, we will use a case study to describe the quality management system in a factory. For the product development preparation domain, the DSM for 14 inputs was compiled, which characterizes trends not only in document control and review activities but also in the company strategy and policy statements as well as management competence in product development preparation. It should be mentioned here that some rules of completing the matrixes presented in section 4.4 are repeated for reasons of reading clarity. There is no need to arrange inputs in the same order as sequenced by the mathematical treatment of the matrix. All inputs must only be preliminarily numbered to give a possibility to involve the interaction strength between inputs in the matrix and therefore the numbers of inputs must be the same on the vertical and horizontal axes. Synergy dimensions are introduced to the DSM in the form of the evaluation of inputs interactions power (synergy) of the parameters and processes on a 3-step scale. For quality management activities, the next scale is suitable: 2 – interaction is strong, 1 – interaction is moderate, 0 – interaction is practically absent. The direction of interaction is very important here and in case of use of results of a previously completed task in the following one, only the first should be written into the matrix.

Fig. 5.6 shows the activity-based matrix for product development preparation already allocated to sequencing transformation. In this transformation process, activities are arranged such that all interactions can be moved under the diagonal that leads to the possibility to use the information of previously completed actions in a chain of activities. Sometimes, parallel actions are necessary with over diagonal activities. In some cases, the solution of the current task needs some feedback information from the later activity and those bounded tasks are grouped into outlined blocks.

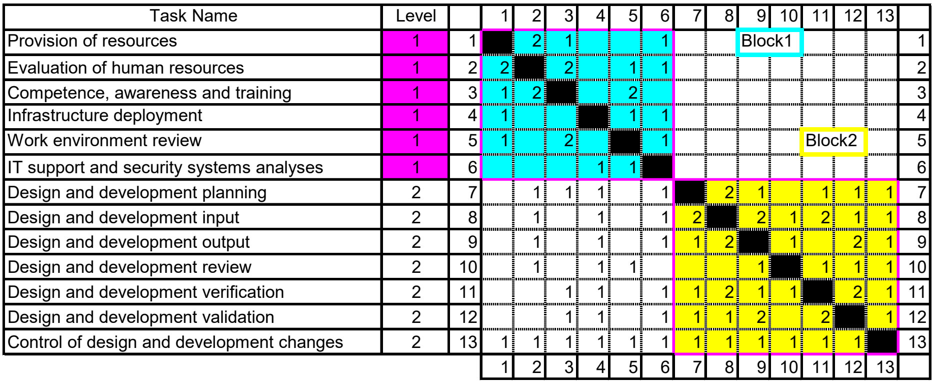


Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Documentation review	1	1	■	1	2			Block1									1
Control of documents	1	2	1	■	2												2
Control of records	1	3	2	2	■												3
Management involvement	2	4	1			■		2	2	1	1			Block2			4
Customer focus	2	5					■	1		1							5
Outlining the company's quality policy	2	6		1	1	2	1	■	2	2	1						6
Product strategy planning	2	7	1			2		2	■	2	1						7
Quality objectives	2	8	1					2	2	■	1			Block3			8
Quality management system's planning	2	9		1	1	1		1	1	1	■						9
Responsibility and authority	3	10		1	1						1	■	2		2	1	10
Management representative	3	11			1	1		1		1		2	■	1		1	11
Internal communication	3	12	1		1					1	1		1	■			12
Management reviews input and output	3	13		1		1		1	1	1	1	2			■	2	13
Management reviews timing	3	14	1	1		1		1		1			1		2	■	14
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	

Figure 5.6 Product development preparation matrix (Hindreus, 2009)

Now we have reached the first goal – all activities are sequenced and grouped on the levels, which mark the decision-making steps. All three levels in the matrix form an invisible block of the SWOT analysis, where on the first level; the focus is on the company's documentation control and on the third level, on management responsibilities and internal communication. On the second level, it is necessary to provide the analysis of quality policy and strategy and the way how all problems with the management review and competence problems should be solved. The expected outcome from the synergy-based approach of this matrix analysis is to work out the company's external and internal product policy and activities to manage risks in the conditions of decreasing or increasing market.

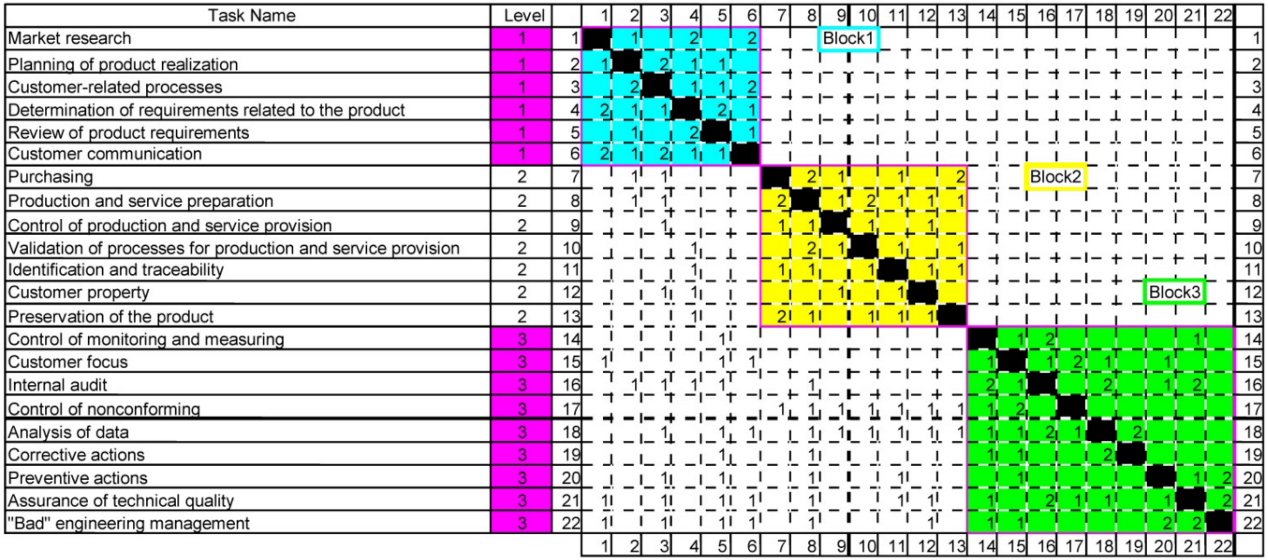
Fig. 5.7 presents the design and resource management DSM after sequencing. On the first level, the block of the resource and infrastructure management is formed. The second block is a real design and development matrix where all important design quality preconditions are presented. The expected outcome of this analysis is a proposal for the structure of a more excellent product at a moderate price rise.



Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	
Provision of resources	1	1	■	2	1			1			Block1					1
Evaluation of human resources	1	2	2	■	2		1	1								2
Competence, awareness and training	1	3	1	2	■		2									3
Infrastructure deployment	1	4	1			■	1	1								4
Work environment review	1	5	1		2		■	1					Block2			5
IT support and security systems analyses	1	6				1	1	■								6
Design and development planning	2	7		1	1	1		1	■	2	1		1	1	1	7
Design and development input	2	8		1		1		1	2	■	2	1	2	1	1	8
Design and development output	2	9		1		1		1	1	2	■	1		2	1	9
Design and development review	2	10		1		1	1				1	■	1	1	1	10
Design and development verification	2	11			1	1		1	1	2	1	1	■	2	1	11
Design and development validation	2	12			1	1		1	1	1	2		2	■	1	12
Control of design and development changes	2	13	1	1	1	1	1	1	1	1	1	1	1	1	■	13
			1	2	3	4	5	6	7	8	9	10	11	12	13	

Figure 5.7. Design and resource management matrix (Hindreus, 2009)

Fig. 5.8 shows the product realization and its analysis of DSM. The focus of this matrix is on choosing the most suitable way for the realization of these functions selected for the analysis of the previous matrix. On the first level, all market and customer related activities are gathered. On the second level, main attention is on production and service planning. The third level is fully focused on the control and monitoring activities.



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	
Market research	1	1	■	1		2		2			Block1														1
Planning of product realization	1	2	1	■	2	1	1																		2
Customer-related processes	1	3		2	■	1	1	2																	3
Determination of requirements related to the product	1	4	2	1	1	■	2	1																	4
Review of product requirements	1	5		1		2	■	1																	5
Customer communication	1	6	2	1	2	1	1	■																	6
Purchasing	2	7		1	1				■	2	1		1		2			Block2							7
Production and service preparation	2	8		1	1				2	■	1	2	1	1	1										8
Control of production and service provision	2	9			1				1	1	■	1		1											9
Validation of processes for production and service provision	2	10				1				2	1	■	1		1										10
Identification and traceability	2	11				1			1	1		1	■	1	1										11
Customer property	2	12			1	1					1		1	■								Block3			12
Preservation of the product	2	13				1			2	1		1	1	1	■										13
Control of monitoring and measuring	3	14					1									■	1	2					1		14
Customer focus	3	15	1				1	1								1	■	1	2	1		1			15
Internal audit	3	16		1	1	1	1			1						2	1	■		2		1	2		16
Control of nonconforming	3	17							1	1	1	1	1	1	1	1	2		■						17
Analysis of data	3	18			1		1	1		1	1	1	1	1	1	1	1	2	1	■	2				18
Corrective actions	3	19					1			1						1	1			2	■				19
Preventive actions	3	20			1		1			1			1				1					■	1	2	20
Assurance of technical quality	3	21	1		1		1	1		1			1	1		1		2	1	1		1	■	2	21
"Bad" engineering management	3	22	1		1		1	1		1				1		1	1					2	2	■	22
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	

Figure 5.8. Product realization and analysis matrix (Hindreus, 2009)

In summary, the benefit of the above matrix-based analysis is attaining a trustworthy pathway to move ahead in the quality management system planning. In reality, there may be many much more inputs and the sequencing of them may be far behind the brains ability. In this context, indications about interactions that need hard work to introduce the positive synergy are welcome. To avoid negative synergy in teamwork, it is necessary to take action for pressing down the human shortcomings described.

The results of the analysis of human shortcomings may be used for the statistical probability evaluation of the duration for planning the quality management activities. By using appropriate mathematical tools (Cho&Eppinger, 2001), it is possible to schedule the dispersed activities by levels, grouping them into sub-matrixes of coupled tasks and take into consideration the time for iterations, reworks and learning at the preparation of the company for quality certification. It is possible to use the Latin Hypercube Sampling (LHS) and parallel discrete event simulation to incorporate the uncertainty of the expected duration of the tasks on three levels: optimistic, most likely or pessimistic. Fig. 5.9 shows the result of the probability analysis of the duration of the activity-based product development preparation matrix block 2 (see Fig. 5.6).

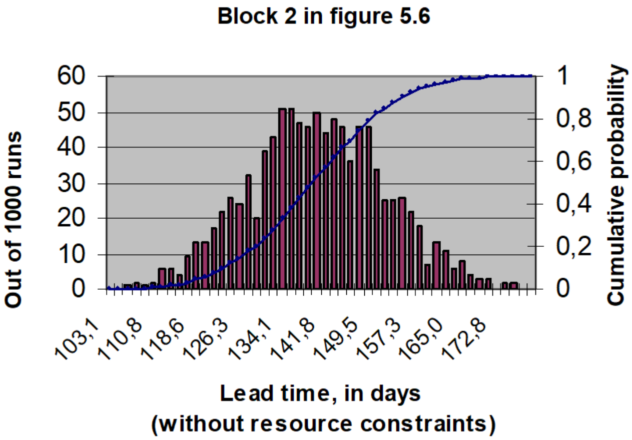


Figure 5.9. Prognosis of the duration of the certification process (Hindreus, 2009)

It is quite time-consuming to compose a useful and suitable DSM matrix; generally, it may turn out to be a great challenge to the quality management team as the professional knowledge required is made up of product architecture, the product development and the quality management process. The question of the competence level required to use the proposed simulation method arises, although all of these mathematical tools are available in open mathematical software. Therefore, to exploit the possibilities of the proposed approach to the full, an experienced professional team is required. However, no methodology is so adequate that it can suit any competence level of the team. In conclusion, the main key to reducing the effects of negative synergy is to increase the synergy of teamwork and the team's overall core competence to empower positive synergy.

In summary, the flexibility and suitability of the described approach for setting up synergy-based priorities should be underlined. This approach makes it possible to realize the filtration principles of negative synergy and to reach the optimal synergy level set by the market in minimal time. Successful use of the philosophy of synergy-based thinking in the quality management area provokes a perspective for successful integration of it with the product design quality.

5.5. Synergy-based approach to quality assurance system

T. Hindreus, A. Martin

So far the proposed synergy-based adaptive design methodology has been tested for the first two DSM matrixes (see section 4.4) where the testing object was the upgrading of the high accuracy pneumatic positioning device. However, before the integration of product quality and management quality schemes, it is obviously necessary to test the synergy-based design methodology as a case study in its full extent and in the real industrial environment when all design parameters, market conditions and human shortcomings are taken into account.

Only one suitable database for this purpose – the database of light fitting design and production (Martin et al., 2006) – was available for the research team. Despite seeming simplicity, modern light fittings are a clever integration of mechanical support structure with optics, thermal engineering and electronics. As a basis, the database of human and technical shortcomings containing more than 700 descriptions was used. Therefore, it is appropriate to test the entire adaptive synergy-based design methodology on the basis of light fitting design to use the pattern of adaptive design methodology (Kaljas, 2005). Fig. 5.10 shows the arranged synergy-based model for the design of light fittings. In the upper part of the illustration, the specific content of design domain matrixes is opened.

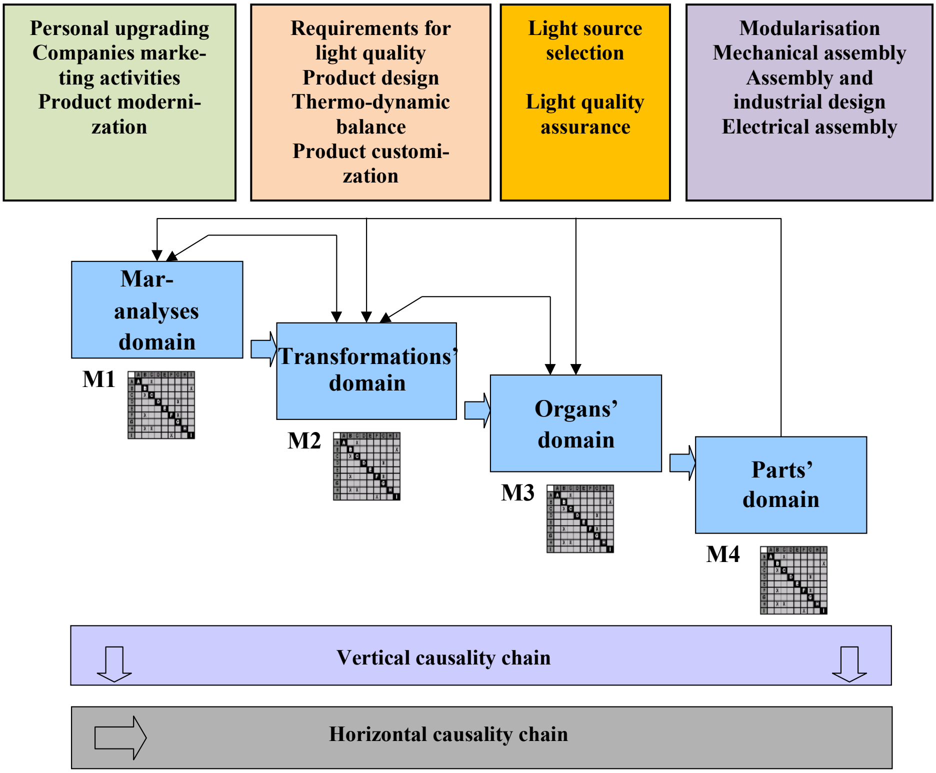


Figure 5.10. The integrated model for light fittings system design (modified from Kaljas, 2005)

For the matrix of the market analysis domain, the DSM for 16 inputs was compiled (see Fig. 5.11), which characterizes trends in the present market environment, the product strategy of the company and its personnel's competence in product development. The expected outcome from the synergy-based approach of the analysis of this matrix is to work out the company's external and internal product policy and activities to manage risks in the conditions of the decreasing or increasing market. The guidelines for completing the information in matrixes are the same as described in section 5.4.

Task Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Market expects smaller size of light fittings	1	■	1					2	1		1	1	2	1	1	1	
Market expects better quality of lightening	2	1	■					2			1	1	2	1	1		
Market needs cheaper light fittings	3	1		■	1			2			2	1	1	1		1	
Market needs multifunctional light fittings	4			1	■			2		2	2	1		1		1	1
Market expects light fittings with easy mounting	5					■		2	1		1			1		1	
Simplified service of light fittings	6				1		■	2	1		1			1		1	
To increase the light fittings customization	7					1	1	■	2		2	2	1	1	1	1	
Positioning of the product on a higher level in the market	8								■	1	2	2	2	1	2	1	1
Bought-in technology transfer	9									■						1	1
Companies' market share expansion strategy	10								2		■	2	2	1			
Empowering of companies' product development capability	11								2		2	■	2		1	2	2
Competence level of companies' needs to be increased	12												■		2	1	1
Product needs modernization	13													■	1	1	1
Product development needs advanced scientific research	14												2	1	■		1
Development of synergy based communication ability	15															■	2
Development of the inside synergy of the team members	16															2	■

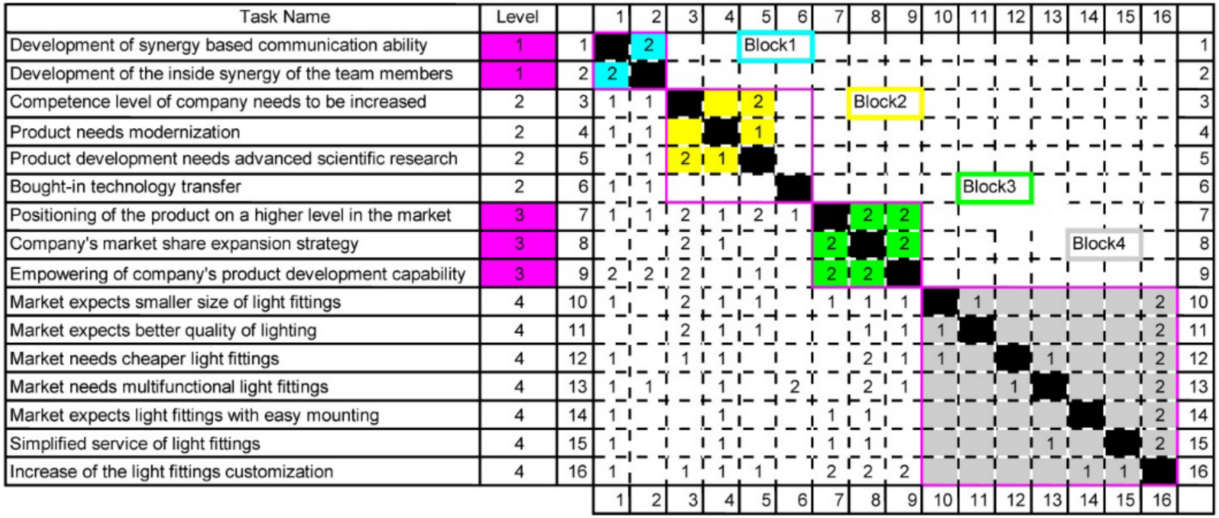
Figure 5.11. Activity-based market relations DSM before sequencing (Hindreus, 2009**)**

In Fig. 5.12, the previous matrix has been allocated to sequencing transformation. However, it is necessary to remember the main purpose – to reach the optimal synergy in prioritized interactions on all levels of problem-solving. Now we have reached the first goal – all activities are sequenced and grouped on the levels, marking the decision-making steps. In the present case, on the first level, it is necessary to provide an analysis of the design team's competence where all problems with product development capability and personnel upgrading problems should be solved. The two next levels form an invisible block of the SWOT analysis where on the second level, the focus is on the company's inside and on the third level, on the outside activities on the market. On the last level, the decisions have to be made about the necessity of product modernization.

Fig. 5.13 presents the parameter-based transformation domain DSM after sequencing. The expected outcome from this matrix analysis is a proposal for the structure of a more excellent device at a moderate price rise. On the first level, the block of the initial light quality parameters is formed. The second block is a real design matrix where all important design parameters supporting the performance of the product are presented. The focus of the activities on this level is the key problem for light fittings – to solve thermodynamic problems by making a compromise between its dimensions and the limited temperature level for its components. The last level carries the feature of the output parameters where variations of the principles of montage and additional functions of protection are estimated.

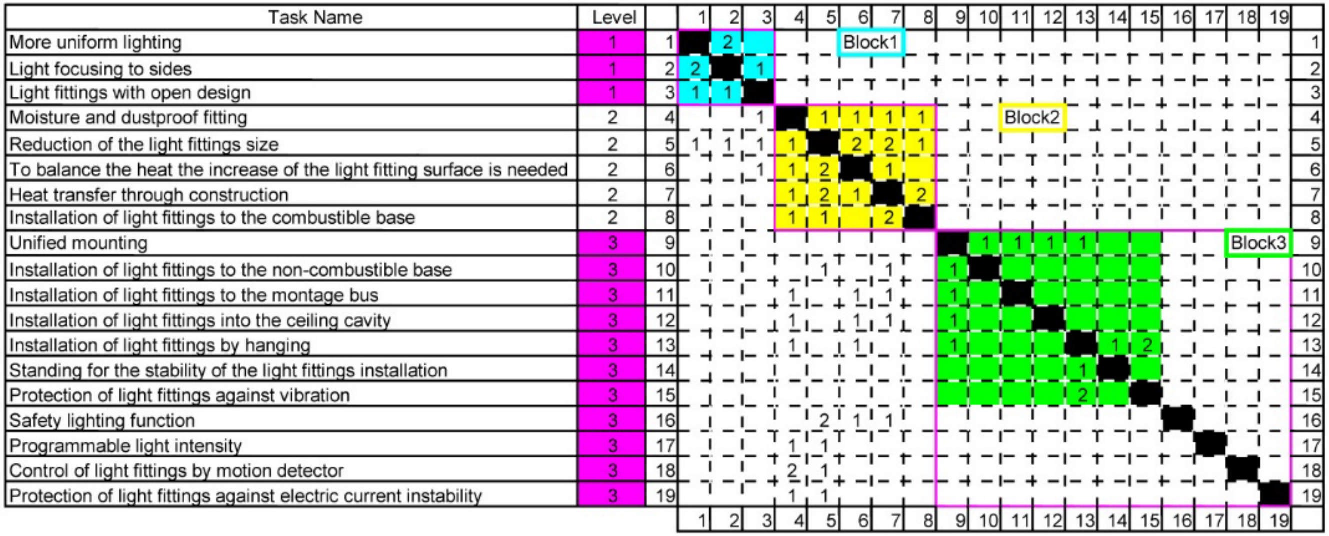
Fig. 5.14 shows the organs' domain DSM. The focus of this matrix is to choose the most suitable physical effects for the realization of these functions selected in the analysis of the previous matrix. On the first level, all assembly problems are gathered, including the way of its allocation to the producing and service demands. On the second level, main attention is paid to choosing the physical principle of the light source integrated with housing, reflection quality, and electrical communications. The third level is fully focused on light quality, forming systems using different reflection principles. Thus, the solution of the described problems paves the way to the detailed design and completing the assembly drawings.

Figure 5.15 presents the last DSM – that of the details' domain. It is reasonable to allocate this matrix to structuring, as it also serves the interests of product modularization. For the present case, only three tasks may be differentiated – mechanical and electrical design with some interfaces between these blocks for carrying the idea of technologies integration.



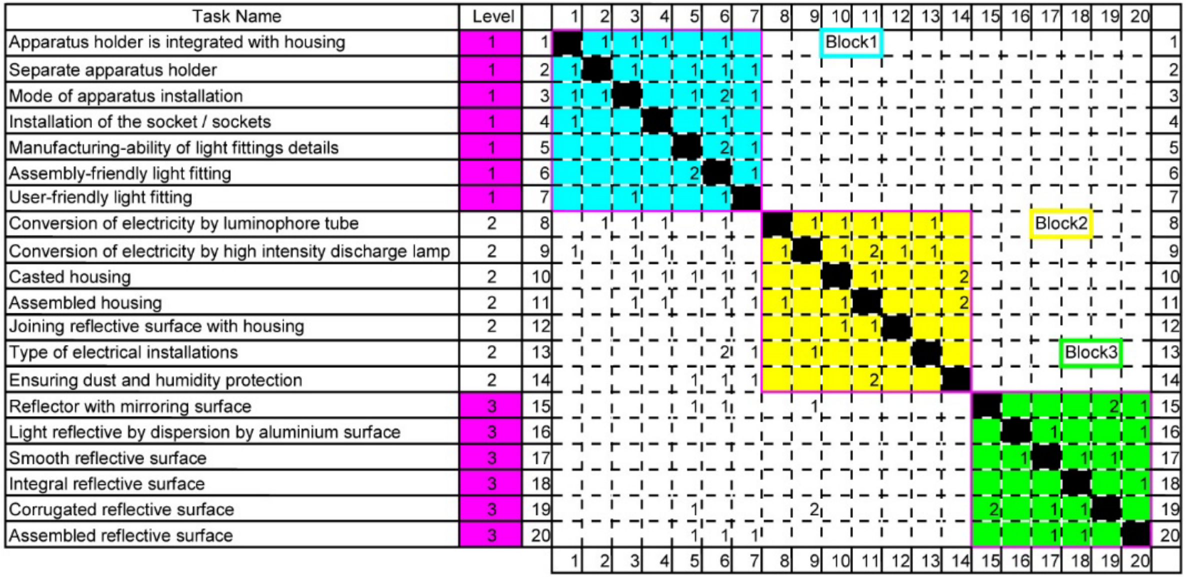
Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Development of synergy based communication ability	1	1	■	2															1
Development of the inside synergy of the team members	1	2	2	■															2
Competence level of company needs to be increased	2	3	1	1	■		2												3
Product needs modernization	2	4	1	1		■	1												4
Product development needs advanced scientific research	2	5		1	2	1	■												5
Bought-in technology transfer	2	6	1	1				■											6
Positioning of the product on a higher level in the market	3	7	1	1	2	1	2	1	■	2	2								7
Company's market share expansion strategy	3	8			2	1			2	■	2								8
Empowering of company's product development capability	3	9	2	2	2		1		2	2	■								9
Market expects smaller size of light fittings	4	10	1		2	1	1		1	1	1	■	1					2	10
Market expects better quality of lighting	4	11			2	1	1			1	1	1	■					2	11
Market needs cheaper light fittings	4	12	1		1	1				2	1	1		■	1			2	12
Market needs multifunctional light fittings	4	13	1	1		1		2		2	1			1	■			2	13
Market expects light fittings with easy mounting	4	14	1			1			1	1						■		2	14
Simplified service of light fittings	4	15	1			1			1	1					1		■	2	15
Increase of the light fittings customization	4	16	1		1	1	1		2	2	2					1	1	■	16
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	

Figure 5.12. Activity-based market analysis DSM after sequencing (Hindreus, 2009)



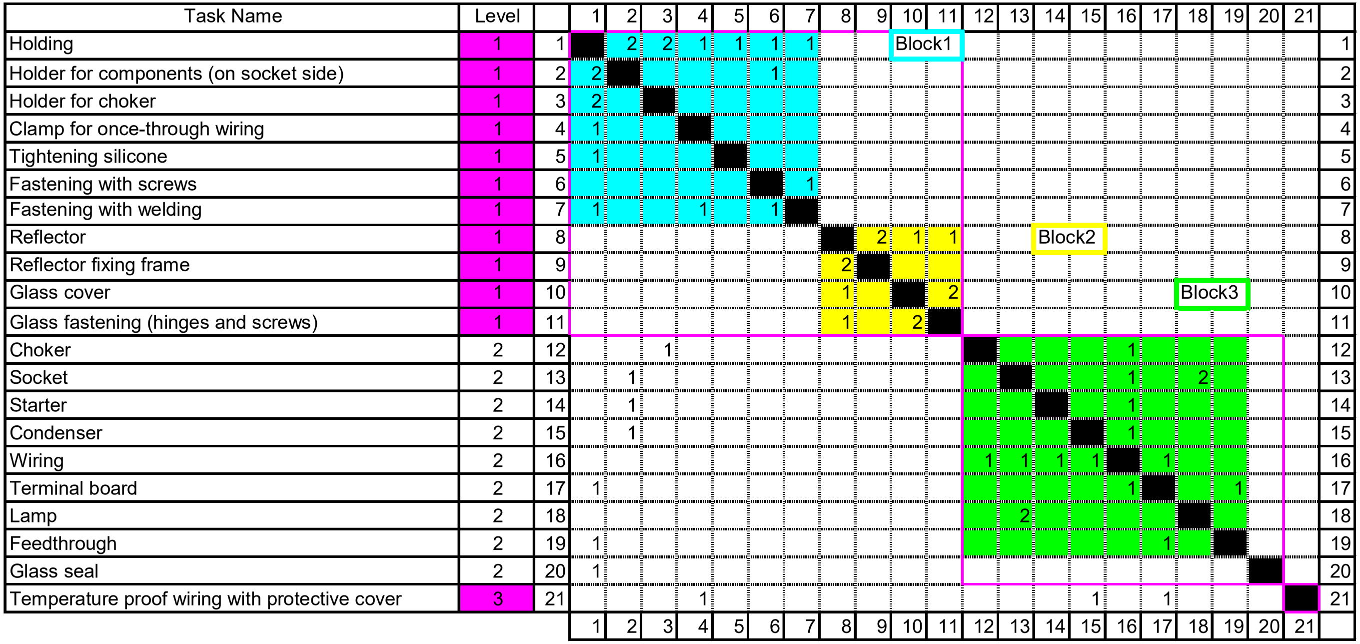
Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
More uniform lighting	1	1	■	2				Block1														1
Light focusing to sides	1	2	2	■	1																	2
Light fittings with open design	1	3	1	1	■																	3
Moisture and dustproof fitting	2	4			1	■	1	1	1	1			Block2									4
Reduction of the light fittings size	2	5	1	1	1	1	■	2	2	1												5
To balance the heat the increase of the light fitting surface is needed	2	6			1	1	2	■	1													6
Heat transfer through construction	2	7				1	2	1	■	2												7
Installation of light fittings to the combustible base	2	8				1	1		2	■												8
Unified mounting	3	9									■	1	1	1	1					Block3		9
Installation of light fittings to the non-combustible base	3	10					1		1		1	■										10
Installation of light fittings to the montage bus	3	11				1		1	1		1		■									11
Installation of light fittings into the ceiling cavity	3	12				1		1	1		1			■								12
Installation of light fittings by hanging	3	13				1		1			1				■	1	2					13
Standing for the stability of the light fittings installation	3	14													1	■						14
Protection of light fittings against vibration	3	15													2		■					15
Safety lighting function	3	16					2	1	1									■				16
Programmable light intensity	3	17				1	1												■			17
Control of light fittings by motion detector	3	18				2	1													■		18
Protection of light fittings against electric current instability	3	19				1	1														■	19
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	

Figure 5.13. Parameter-based transformations' DSM after sequencing (Hindreus, 2009)



Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Apparatus holder is integrated with housing	1	1	■	1	1	1		1															1
Separate apparatus holder	1	2	1	■	1		1	1	1														2
Mode of apparatus installation	1	3	1	1	■		1	2	1														3
Installation of the socket / sockets	1	4	1			■		1															4
Manufacturing-ability of light fittings details	1	5					■	2	1														5
Assembly-friendly light fitting	1	6					2	■	1														6
User-friendly light fitting	1	7			1			1	■														7
Conversion of electricity by luminophore tube	2	8		1	1	1		1		■	1	1	1		1								8
Conversion of electricity by high intensity discharge lamp	2	9	1		1	1		1		1	■	1	2	1	1								9
Casted housing	2	10			1	1	1	1	1			■	1			2							10
Assembled housing	2	11			1	1		1	1	1		1	■			2							11
Joining reflective surface with housing	2	12										1	1	■									12
Type of electrical installations	2	13						2	1		1				■								13
Ensuring dust and humidity protection	2	14					1	1	1				2			■							14
Reflector with mirroring surface	3	15					1	1			1						■				2	1	15
Light reflective by dispersion by aluminium surface	3	16																■	1			1	16
Smooth reflective surface	3	17																1	■	1	1		17
Integral reflective surface	3	18																		■		1	18
Corrugated reflective surface	3	19					1				2						2		1	1	■		19
Assembled reflective surface	3	20					1	1	1										1	1		■	20
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	

Figure 5.14. The organs' domain DSM after sequencing (Hindreus, 2009)



Task Name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
Holding	1	1	■	2	2	1	1	1	1			Block1												1
Holder for components (on socket side)	1	2	2	■				1																2
Holder for choker	1	3	2		■																			3
Clamp for once-through wiring	1	4	1			■																		4
Tightening silicone	1	5	1				■																	5
Fastening with screws	1	6						■	1															6
Fastening with welding	1	7	1			1		1	■															7
Reflector	1	8								■	2	1	1			Block2								8
Reflector fixing frame	1	9								2	■													9
Glass cover	1	10								1		■	2							Block3				10
Glass fastening (hinges and screws)	1	11								1		2	■											11
Choker	2	12			1									■				1						12
Socket	2	13		1											■			1		2				13
Starter	2	14		1												■		1						14
Condenser	2	15		1													■	1						15
Wiring	2	16												1	1	1	1	■	1					16
Terminal board	2	17	1															1	■		1			17
Lamp	2	18													2					■				18
Feedthrough	2	19	1																1		■			19
Glass seal	2	20	1																			■		20
Temperature proof wiring with protective cover	3	21				1											1		1				■	21
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	

Figure 5.15. The details' domain DSM after structuring (Hindreus, 2009)

Thus, the trustworthy roadmap for the design process has been created, which enables keeping a comprehensive overview of the decision-making process. As a matter of fact, for this case, we have been able to distinguish 12 groups of decision-making levels and 75 design tasks with 279 interactions where we have to look for the possibility of synergy-based integration. Every block forming as the result of mathematical sequencing, can be supplied the probabilistic prognosis of optimistic, most likely or pessimistic duration. So far we have collected enough evidence that the synergy-based methodology is a suitable tool for the integration of different technologies (Hindreus et al., 2008b).

The final goal in this quality-synergy debate is to clarify the possibility of integration of the quality management system with the product design quality concept into an overall effective quality assurance system in the synergy-based manner. It is not superfluous to note that the two mentioned systems are so far somewhat disunited. The aim of the product design quality concept is to choose a methodology that enables building the quality into the product from the first steps of its development. The outcome of this effort is the product price and the performance that are competitive on the market. The quality management system has to assure the product quality in a wider framework: qualification of producing personnel, quality of used production equipment and tooling, effectiveness of the quality management system, etc.

For any systems integration, it is necessary to find a suitable meta-tool able to describe all specific features of both systems in a common language. In the previous section, we concluded that a suitable meta-tool for integration may be found in the synergy-based approach. The synergy-based approach opens a possibility to integrate under one umbrella market conditions, design activities and quality management activities, which are all based on human behaviour (Hindreus&Reedik, 2008a). There is an optimistic perspective that the application of the synergy-based approach to engineering design and quality management makes it possible to develop a new framework of adaptive quality assurance tools based on the level of competence and expert knowledge of the team.

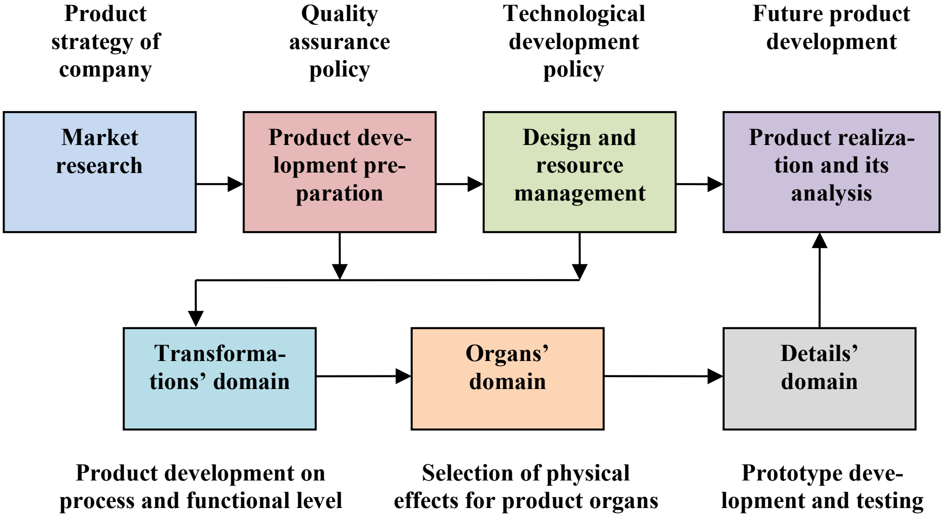


Figure 5.16. Integrated synergy-based scheme of total quality assurance (Hindreus, 2009)

The integrated synergy-based scheme of quality assurance is shown in Fig. 5.16. Now we have a powerful meta-tool allowing operating with seven matrixes, in which the information of synergy relations between their elements along with a scheduled roadmap of the activities is stored. As a result, a new product can reach the market at minimal possible time. The initial matrix is that of market research that allows for benchmarking the company's and its product position on the market and finding out the possibilities to empower this position. It is required to identify the quality assurance policy in the product development preparation phase, which usually is the result of the formed product strategy of the company. The design and resource management stage forms the technological development policy, which is the basis for product realization and its analysis. Real integration of product design quality into the overall quality assurance system undergoes matrix-based analysis of the domains of transformations, organs and details. After passing through the last domains, the product prototype will be physically realized and tested.

The practice of preparing companies for the certification (Hindreus, 2009) of quality assurance systems according to the ISO standards is mostly based on the knowledge of the consultants who know the requirements of the standards but very often they are unaware of the organizational problems of the companies. The proposed synergy-based methodology can help to increase the readiness level of the company for certification. In reality, the success of the quality management system of the company also depends on many other factors like market conditions, customer requirements, legal issues between companies, and product quality. The synergy-based approach to quality assurance takes into account all known obstacles and integrates them into one system. Thus, a firm basis is created, which guarantees that after implementing the synergy-based approach, the company will be able to meet the requirements of certification bodies.

In summary, a suitable basis has been developed to speed up the integration of the still somewhat disunited product quality and quality management concepts into an overall effective quality assurance system (Hindreus et al., 2012). In this way, it is possible to construct a hypothetical sample certification process with minimum nonconformities and observations. According to the rules of the certification process, the classical testing of the developed quality assurance framework in practice is impossible, as the certification body has to be independent. This testing is possible only when applying the proposed approach to the results of the provided certification processes. Therefore, the effectiveness of the synergy-based quality assurance system was verified by organizing a follow-up test on the basis of the existing certification conclusions; the result was clearly positive. The synergy-based approach paves the way for the development of an optimal adaptive quality assurance system, in which the decision-making algorithm depends on the maximum effective use of the expert knowledge and competence of the company personnel. It allows for synthesizing their roadmap algorithm for moving ahead on the way of the synergy-based quality assurance process.

6. SYNERGY DEPLOYMENT IN MULTI-AGENT MODULAR SYSTEMS

M. Sarkans, M. Eerme, V. Reedik, L. Roosimölder

6.1. Overview of complex systems synthesis and optimization

In the preceding chapters, the main focus was on the integration of different technologies and human resources. Our next question is – how synergy-based thinking philosophy can be applied to the modularization of the products and manufacturing processes, which at first sight seems to be a contradicting process. To solve this dilemma, upon request from industry, doctoral research of Martinš Sarkans (Sarkans, 2012) was initiated.

It is obvious that today's industry is moving towards knowledge-intensive products and processes. As products are growing more intricate, by integrating knowledge from different domains (mechanics, physics, chemistry, electronics, informatics, etc.), they become complex systems. To emphasize the complexity of today's products/systems, for instance, we indicate here that a modern passenger car consists of about 10,000 unique parts and an airliner of more than 130,000 components. To realize these systems, about 850/1,400 and 6,800/10,000 internal/external development team members must concentrate their efforts, knowledge and experience at peak time (Ulrich&Eppinger, 1995). The production processes of these unique parts also require complex production systems (e.g., robot welding cells) to be implemented with an increasing number of subcontractors. Therefore, to secure success on the global market, the need for suitable methodologies for managing the complexity is increasing.

The systems theory has long been concerned with the study of complex systems, which tend to be high-dimensional, non-linear and hard to model. INCOSE (International Council on Systems Engineering) defines a system as follows: "A system is a construct or collection of different elements that together produce results not obtainable by the elements alone (important reference to the definition of synergy!). The elements or parts can include people, hardware, software, facilities, policies, and documents, that is, all things required to produce systems-level results. The results include system level qualities, properties, characteristics, functions, behaviour and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts, that is, how they are interconnected" (INCOSE, 2010). This look is very encouraging to the further use of synergy-based thinking and enough detailed in its content to design the image of complex systems and their management.

Systems engineering encourages the use of tools and methods to better comprehend and manage complexity in systems and to use methodologies by dividing complex systems into appropriate parts or its modularization (Blackenfelt, 2001). Complex systems consisting of multiple elements with nonlinear interfaces cannot be analysed without the involvement of synergetics philosophy (Haken, 1997). Synergy between systems elements reveals only under the conditions of nonlinear complexity and it opens a way to the meta-level tools for the optimization of those systems structure. This optimization may be supported only by tools of soft computing integrating fuzzy technology, artificial neural networks and genetic algorithms (Ivancevic&Ivancevic, 2008). The same flexibility allows also the independent development of modules, which is useful in concurrent design or overlapped product development (Roemer et al., 2000).

In the following, the modular systems terminology will be briefly introduced for better understanding of the further discussions. **Product architecture** is a concept of how a company understands their products, e.g., a formal model that explains the partitioning of the product, main benefits of the use of modular systems in an view, and the relations between different parts of the product. The central position in the product architecture is **product platform**. The term "platform" comes from the car industry. In the 1920s -1930s, major American car companies launched multiple brands to be able to meet more varied public demands (Tichem, 1997). There exist many different definitions of product platform; however, the following seems to be the most promising in the synergy-based thinking context: "The product platform is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced" (Meyer&Lehnerd, 1997).

Thus, to define a modular platform, the **interfaces** between the **modules** should be defined. Some authors see the interfaces between modules as the core issue of modularity. The **module** is a structurally independent building block of a larger system with well-defined interfaces. A module is fairly loosely connected to the rest of the system, allowing independent development of the module as long as the interconnections at the interfaces are well thought (Baldwin&Clark, 2000; Ericsson&Erixon, 1999). The interface includes the fundamental and often also the incidental interactions between the modules (Pimmler&Eppinger, 1994). By designing a module, the interfaces have to be stable over the time, robust to variation, simple and have to be defined early in the development process. Interactions between modules – informational and geometrical - may also be classified according to strength; the classes are weak, semi-strong or strong, which is close to synergy-based thinking.

As the technological foundation of **product families**, a product platform is the physical implementation of a technical design that serves as the base architecture for a series of derivative products. A product family (also known as product portfolio) is a set of variants of a product to fulfil a certain set of customer needs. The product platform also embraces manufacturing technology and processes employed in production (Meyer&Lehnerd, 1997; Avak, 2006).

When implementing a product platform, the issue of the **reuse** of approved modules is important as it enables one to reduce the design time of new products, increase the quality of the solutions and increase the efficiency of the product platform. Reuse means that something (properties, solutions, etc) repeats itself in a new product, and in different variants and models of a product. This something can be: complete building units, groups of parts, design elements, a user interface etc. (Duffy et al., 1998; Sreeram&Chawdry, 1998).

Now we need to find out how the experience of the use of the TDD/DSM approach described above is meeting the demands of developing complex multi-agent systems. At first sight, their usability in these applications is based on their ability to represent the complex relationships between the components of a system in a compact, visual, and analytically advantageous format. Coordination complexity can be significantly reduced if the elements are clustered or modularized so that their interactions occur predominantly within subsystems rather than between them (Baldwin&Clark, 2000; Rechtin, 1991; Sanchez&Mahoney, 1997). The optimization approach to an activity-based DSM consists in ensuring that the right information is available at the right place at the right time; activities are properly sequenced, relevant constraints and requirements are given as quickly as possible and mistakes are minimized (Otto et al., 2011).

6.2. Case study of expedient modularization

The key problem for product modularization is a rational moment of decisions on the modular structure of the system's design. It cannot be determined at the beginning of design activities and also at closing the development but just-in-time. In our further discussions, we will use the term expedient modularization for this process.

In addition to the particular challenge of a quick response to dynamic customer needs, today's manufacturing industry is facing wide variations and increasing complexity of products together with rapidly changing design and production potentialities. Research in operational management suggests that firms can mitigate the negative impact of product variety on operational performance by deliberately pursuing modularization in the design of product family architectures and platforms. So, modularization as an engineering approach organizes and structures complex products, processes or systems into a set of modules, which can be developed and assembled independent of the final product. Numerous case studies concerning product platforms have been analysed, which point out their advantages and challenges, and demonstrate their ability to save costs and grow their profitability over their competitors (Henderson&

Clark, 1990; Sanderson&Uzumeri, 1995; Meyer&Lehnerd, 1997; Breidert& Welp, 2003; Ishii&Yang, 2003; Preden et al., 2007).

The best way to understand expediency of the modularization is to follow a real case of development of a modular product – a test adapter (see Fig. 6.1) for functional and electrical testing of mobile phones (Sarkans, 2012). Previously, an adapter was designed and produced individually for each testable phone model. The inexpedient number of designed and produced adapters forced to seek ways to reduce the number of different adapters and increase the number of reusable modules. The test adapter is product-specific equipment and the need for a suitable platform increases due to the growing variety of mobile phones. So, first, the advanced test adapter must consist of special functional units that serve as an interface between the tested phone and the measuring device. Module reuse is also considered as an important factor in product platform architecture to speed up the product development of new test adapters.

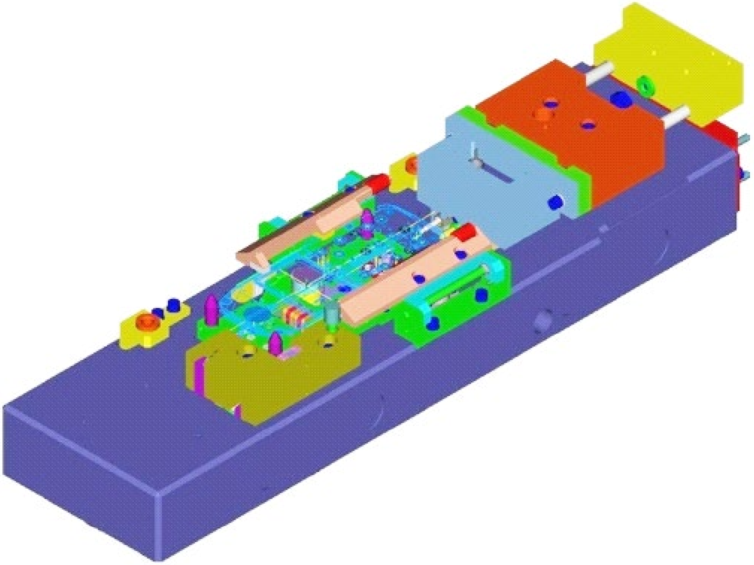


Figure 6.1. Test adapter for mobile phones (Sarkans, 2012)

The tester with an adapter is provided for fully automatic tests of mechanical, RF (Radio Frequency), electrical, audio and visual interfaces of the cellular phones in a repeatable and reliable environment in order to maximize product quality and capacity with minimal labour costs. The creation of a product platform for test adapters by reusing modules is the main goal of the study in (Sarkans&Roosimölder, 2004). Not all modules could be reused for the development of new products; so it is required to select those appropriate. As a result, an updated product platform for test adapters has to be created using fewer original modules. This approach should reduce the development time and production costs when creating new test adapters. For a comparative study, three approaches to the modularization were investigated: functional decomposition, MIM (Module Indication Matrix) and DSM (Dependency Structure Matrix) technology.

During the functional decomposition, the main and support functions common to test adapters of mobile phones were specified as follows. The main functions here are: pushing the power key, pushing the volume key, contacting with the SIM (Subscriber Identity Module), contacting with the battery, contacting with the system connector, etc. Support functions are functions with the help of which the phones are transferred into the working position and these are pushing the system connector, pushing the main test block, connecting the main PCB (Printed Circuit Board) etc. As expected outcomes, the following should be specified: interface type definition, interface strength definition, platform architecture schematics, and module reuse possibilities.

As a result of the analysis, a functional scheme and possible modular adapter architecture was developed (see Fig. 6.2). The modules were defined by the performed functions. On the basis of interactions, the interfaces between the modules were specified. Modularized platform architecture shows module types and relations between the modules and the base module. The platform architecture simplifies selection, allows combining of suitable modules and varying them during the development of a new adapter.

The designed modularized adapter platform will consist of common modules and unique modules, which will be needed for creating new adapters and it allows the reuse of common modules. Adapters have slot type modularity, which refers to a system where each type of module is connected in a certain position by a standard interface. Adapters have a base where modules are fitted to create a new adapter. Modules have strong mechanical interaction with the base.

After the evaluation of the existing modules, a lot of them were found unnecessary and were eliminated from use. As a result, 16 modules were suggested, from which 4 could be integrated in the main test block module. The number of modules used in 36 different adapters before and after modularization is shown in Fig. 6.3, whereas the number of useful modules is significantly reduced (Sarkans&Roosimölder, 2004).

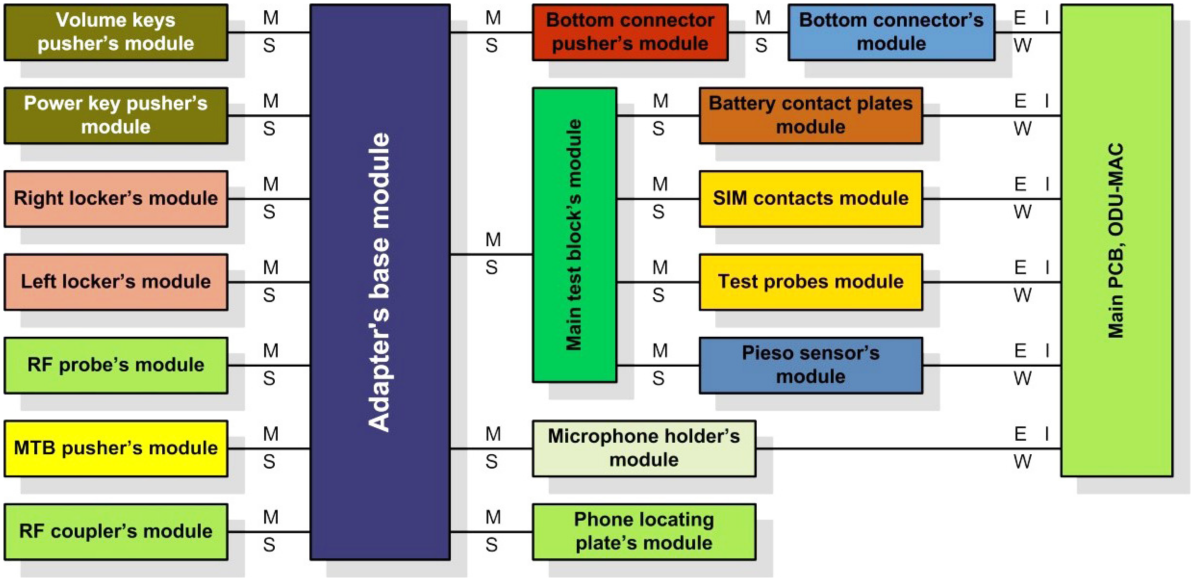


Figure 6.2. Architecture of a modularized adapter platform and interactions between the modules (Sarkans, 2012)
Interaction types: M – mechanical; E – electrical; I – informative
Interaction strengths: W – weak and S – strong
Abbreviations: MTB – Main Test Block; PCB – Printed Circuit Board;
SIM – Subscriber Identity Module; RF – Radio Frequency; ODU-MAC – Open
Modular Connection System

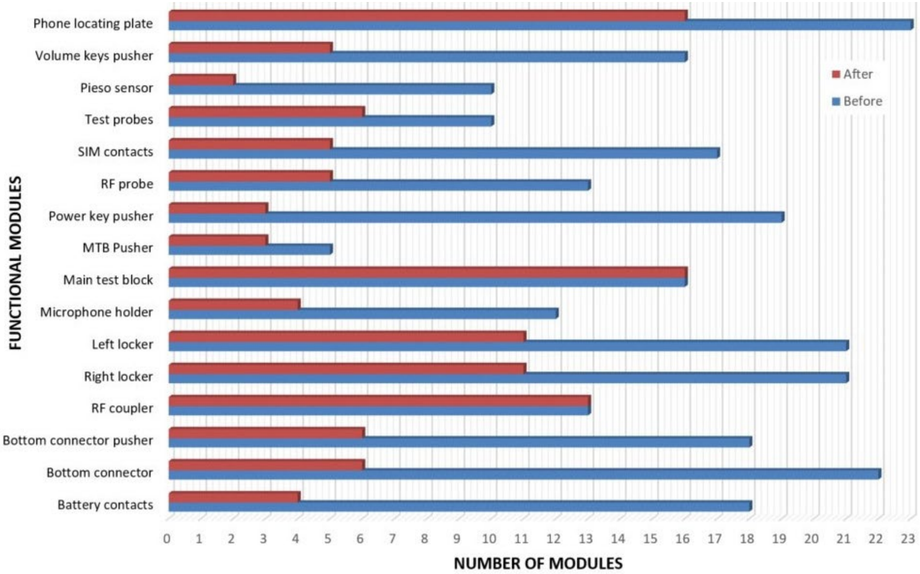


Figure 6.3. Number of modules used in 36 different adapters before and after modularization (Sarkans, 2012)
Abbreviations: MTB – Main Test Block; SIM – Subscriber Identity Module; RF – Radio Frequency

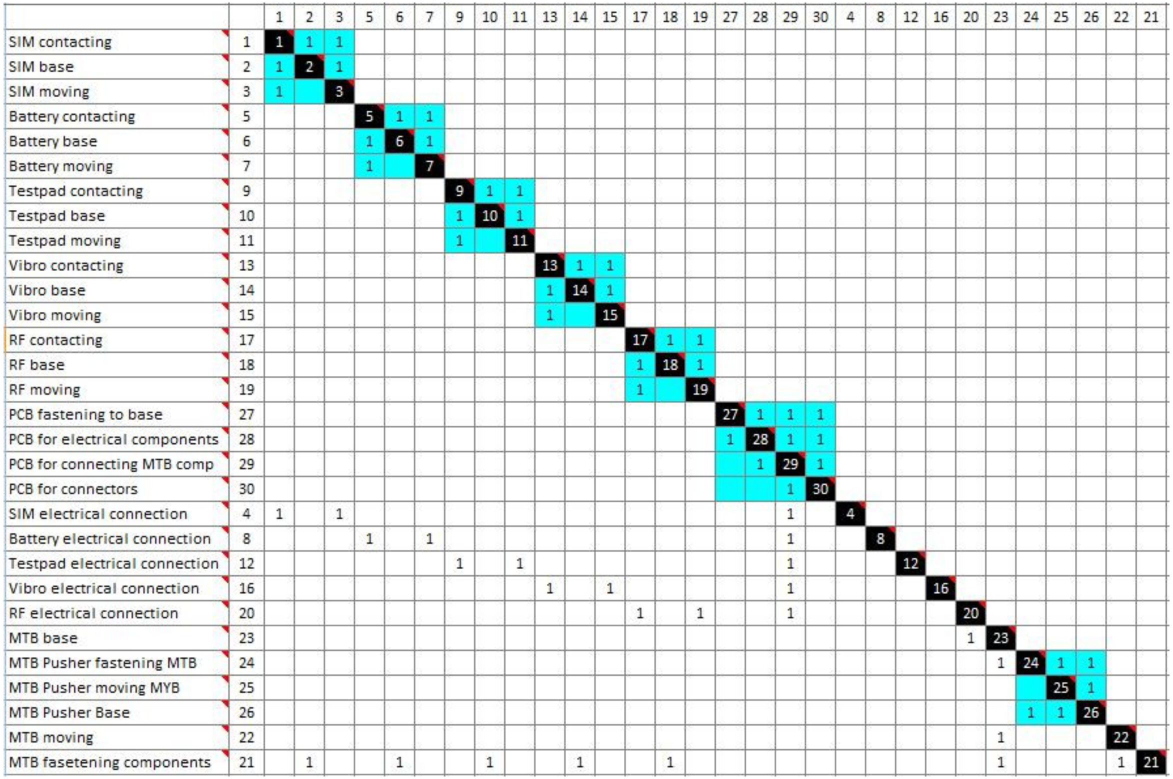
Information about modules analysis accessible for designers, clients, project managers, sales representatives, and other related persons is summarized in the ADB (Adapter Design Book). It is often quite difficult or impossible to make changes in the modular systems that require a wide redesign. In order to reduce the number of necessary redesigns, the interface design must be stable over time and robust to variation, which is a crucial part of the modularization project. Interfaces should be designed with a potential for future needs. ADB is an interactive database situated in the company's server. All the approved modules with connected knowledge are described in the database, which makes it more flexible to use. Also, a 3D model of the adapter's "blank design" is introduced for the designers. The use of ADB has enabled reduction of the design time from eight weeks to four.

For the comparison, the architecture of the test adapter modules was determined in parallel with the help of the Module Indication Matrix (MIM) technology (Erixon, 1998). Using this methodology, a special matrix for the development of the test adapter architecture was completed (see Fig. 6.4). The figure shows that 16 modules have strong enough module drives but four of them could be integrated together. As a result, the final number of modules should be 12. Therefore, it is the same result as that obtained by the previous methodology.

Module driver Functional unit	Carry Over	Technology Push	Planned Design Changes	Different Specification	Styling	Common Unit	Process/Organization	Separate Testing	Strategic Supplier	Service/Maintenance	Upgrading	Recycling	Σ points per function
Volume keys pusher	9		3			6		3		3			**24**
Piezo sensor	9					9				3			**21**
Test probes	9		6	3		6		6		6			**36**
SIM contacts	9					6		6		9		6	**36**
RF-Probe	6		3	3		3	6			6			**27**
Power key pusher	9		3			6		3		3			**24**
MTB pusher	9			3		9				3			**24**
Main test block						6		3		6		6	**21**
Microphone holder	6					6		6		3			**21**
Left Locker	6		6	3		6				3			**24**
Right Locker	6		6	3		6				3			**24**
RF coupler	6		6	6		3		6		6			**33**
Bottom connector pusher	9			3		9				3			**24**
Battery contacts	9					6		9		9		6	**39**
Bottom connector	6					9		9		9		6	**39**
Phone locating plate	3		9			3				6	6		**27**
Σ per module driver	**111**	**0**	**42**	**24**	**0**	**99**	**6**	**51**	**0**	**81**	**6**	**24**	

Figure 6.4. MIM for the test adapter (Sarkans, 2012)
Interactions scale: neutral – 0; weak – 3; moderate – 6; strong - 9
Abbreviations: MTB – Main Test Block; SIM – Subscriber Identity Module; RF – Radio Frequency

The third alternative tool for clustering product architecture and engineering teams is the DSM technology (Pimmler&Eppinger, 1994). The DSM technology was successfully used already in Chapters 4 and 5 of the present book to develop the adaptive design methodology and the quality assurance system. Here the proposed methodology was applied also for the test adapter Main Test Block (MTB) and the corresponding DSM was drawn up (see Fig. 6.5). As the figure shows, the DSM gives a good overview of the MTB structure combined with design activities and offers a key to achieve better synergy in teamwork. As the MTB is a crucial part of the adapter, proper design and faultless operations are required. During the development of the MTB, a mechanical designer,



		1	2	3	5	6	7	9	10	11	13	14	15	17	18	19	27	28	29	30	4	8	12	16	20	23	24	25	26	22	21
SIM contacting	1	1	1	1																											
SIM base	2	1	2	1																											
SIM moving	3	1		3																											
Battery contacting	5				5	1	1																								
Battery base	6				1	6	1																								
Battery moving	7				1		7																								
Testpad contacting	9							9	1	1																					
Testpad base	10							1	10	1																					
Testpad moving	11							1		11																					
Vibro contacting	13										13	1	1																		
Vibro base	14										1	14	1																		
Vibro moving	15										1		15																		
RF contacting	17													17	1	1															
RF base	18													1	18	1															
RF moving	19													1		19															
PCB fastening to base	27																27	1	1	1											
PCB for electrical components	28																1	28	1	1											
PCB for connecting MTB comp	29																	1	29	1											
PCB for connectors	30																		1	30											
SIM electrical connection	4	1		1															1		4										
Battery electrical connection	8				1		1												1			8									
Testpad electrical connection	12							1		1									1				12								
Vibro electrical connection	16										1		1						1					16							
RF electrical connection	20													1		1			1						20						
MTB base	23																								1	23					
MTB Pusher fastening MTB	24																									1	24	1	1		
MTB Pusher moving MYB	25																											25	1		
MTB Pusher Base	26																										1	1	26		
MTB moving	22																									1				22	
MTB fasetening components	21		1			1			1			1			1											1				1	21

Figure 6.5. DSM for the development of the Main Test Block of the test adapter (Sarkans, 2012)
Synergy relations are expressed on a 3-step scale: 0 – indifferent (blank); 1 – moderate; 2 – strong
Abbreviations: MTB – Main Test Block; PCB – Printed Circuit Board; SIM – Subscriber Identity Module; RF – Radio Frequency

an electrical designer, and a RF designer are involved and coordination of their ctivities is necessary. In this DSM approach, the modularization activities pathway is prescribed, which is the basis for pressing down negative synergy and attaining a higher level of positive synergy.

Modularization does not prevent the allocation of synergy but broadens the domain of its successful employment to the production and customization areas (Sarkans et al., 2004). All the results of synergy allocation in engineering design described in Chapters 3-5 are fully applicable also for modularized products. For attaining better synergy in the development process, the principle of expedient modularization is recommended, enabling modularization start at the just-in-time of product development.

6.3. Optimization of the modularization of multi-agent production systems

In the ever growing progress in the product and process development, the medium and small enterprises (SME) happen to be caught into a trap. On the one hand, it is necessary to increase production efficiency, flexibility and profitability implementing production technologies, which are more common in mass-production (robots, CNC-machine tools, etc.). On the other hand, this trend is harassed by the lack of resources (human, financial, etc.). To escape from this situation, the enterprise must use the right strategy for survival through the achievement of synergy in all its activities (Bhangale et al., 2004; Bruccoleri, 2007). Clever modularization of the production system supported by modularization of necessary information and knowledge management may be a life-buoy in this situation.

Manufacturing of cost efficient and client-oriented products by applying robots and manipulators for small batch production and increasing the variety of products are the main directions of production development for SMEs. The majority of tasks done with robots are repetitive and do not change during a long period of time. In parallel, short cycle-times, which are a prerequisite when producing small batches, rapid setup and introduction of new products have been special features at the implementation of robots in SMEs. An extensive international study has been carried out to assess the suitability of robots for SMEs (SMErobot, 2010).

To provide a better description of the complex systems, we introduce here the **concept of agents**. Adopting the agent metaphor in the case of developing complex systems raises both the visibility and abstraction level of interactions between agents. It is obvious that the modelling of systems with multiple agents, both human and manmade, interacting with a diverse collection of hardware and software, is a really complicated task. The term “socio-technical systems” has sometimes been used to feature such systems (Sterling&Taveter, 2009). A socio-technical system has been defined as one that includes hardware and software, has defined operational processes and offers an interface, implemented in software to human users (Weiss, 1999; Bussmann et al., 2004; Seilonen et al., 2009).

A possible system decomposition technique is to divide the system into **layers** associated with related domains. For example, those domains may be product technology, production system, and jig development. As the layers can include different information and knowledge, it is feasible to allocate them also to modularization. Further, the term module or agent is used as a physical (product) or virtual (program) entity. If the human agent is physical or virtual – in reality, he/she is a hybrid entity. To form interconnections between different system layers, two approaches can be simultaneously applied: modules share information and decisions between different layers or it is accomplished by special agents involved. During the implementation process, software agents are introduced, which enables communication (links) between the different layers of the system and the modules.

Practical contributions to the formation of robot welding cells have been analysed in (Matsi et al., 2007; Sarkans&Roosimölder, 2010). The present case study is based on the implementation of experience of a robot-welding cell for mini-loaders Norcar, which were used for welding their base-frames, tools, and lifting beams. The robot welding cell in Norcar-BSB Eesti Ltd is shown in Fig. 6.6 and its configuration is given in Table 6.1. The product portfolio for welding includes more than 40 products. The Metal Inert Gas (MIG) welding process is used for product assembly and 20 different welding indicators are distinguished depending on material thickness and the dimensions of the welded structure. The robot welding cell was designed considering the high flexibility required for the implementation of new products in a short period of time. So, it is necessary to find a methodology for selection of the suitable product for this welding cell.

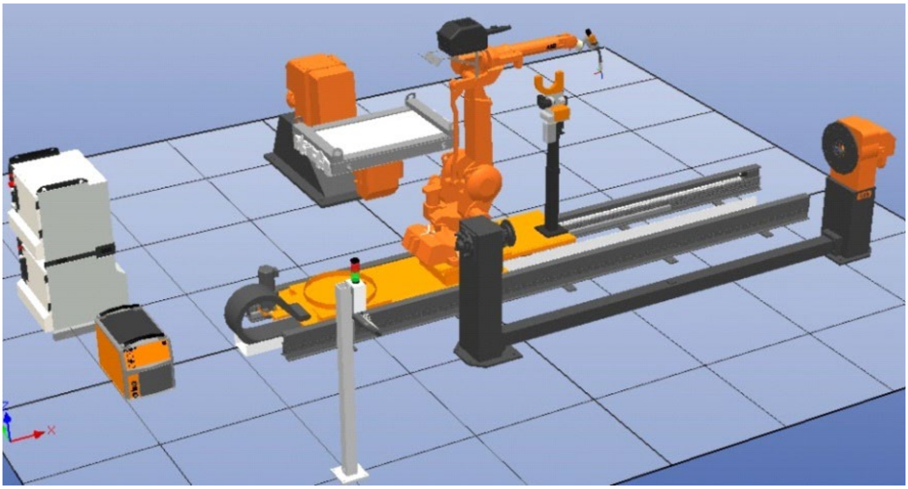


Figure 6.6. Robot welding cell 3D configuration in Norcar-BSB Eesti Ltd (Sarkans, 2012)

Table 6.1. Norcar-BSB Eesti Ltd robot cell configuration (Sarkans, 2012)

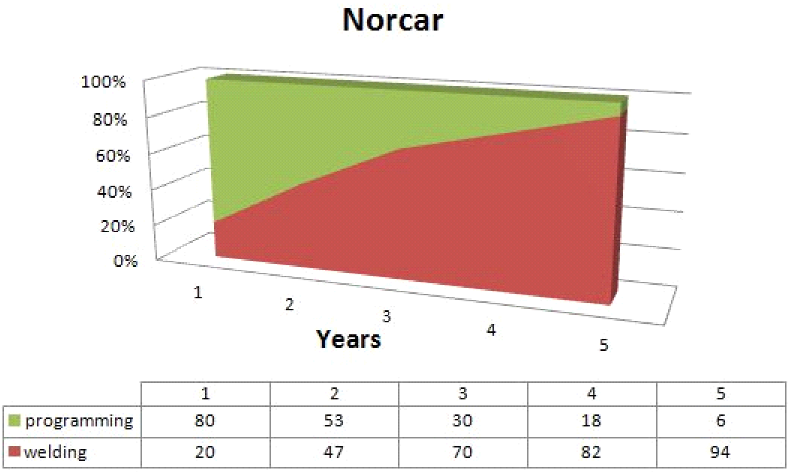
Equipment	**Model**
Welding robot	ABB IRB 2400L
Controller	ABB IRC5 Teach Pendant, software Robot Ware 5.12
Linear track	ABB RTT 2400 L
Positioner 1	ABB IRBP 750 A
Positioner 2	ABB IRBP 750 L
Welding source	ESAB MigRob® 500
Security features	Sick® light curtains

To select components for the robot welding cell, first, in the analysis of the products, appropriate ones were chosen to chart their welding technology. Based on maximum dimensions and the mass of the products, positioners for the robot welding cell were selected. The selected positioners are: ABB IRBP 750A (two axis positioner) and ABB IRBP 750L (one axis positioner). To maximize the active exploitation time of the robot, the two work-piece positioners were selected. To increase the robot’s work portfolio and reachability to different positions, an additional axis was added to the system by selection of linear track ABB RTT 2400L. The selected robot for the system was ABB IRB 2400L.

Based on the analysis of the welding technology and its parameters, the welding equipment Esab MigRob 500 was selected, which enables MIG/MAG (Metal Inert Gas/ Metal Active Gas) welding. This ensures also the welding of thick (15 mm) materials when welding parameters are higher. This configuration of the robot welding cell guarantees the expected flexibility when introducing new products and when the additional development of the cell is needed. One of the ideas during the system selection was to use flexible manufacturing, and the cell was supplied with roller-tables, where the product can be automatically fed to the robot work zone.

Before the purchase of system elements, the whole system was simulated in the ABB RobotStudio 3D computer software environment. After the purchase, the components of the welding cell were assembled and their functionality was tested in the Norcar factory, Finland, where all the components were linked together and tuned. Welding parameters were selected and robot programs were made for two of the products (adapter, lifting beam). In Norcar BSB Eesti Ltd, the implementation process of the robot welding cell continued. Additional products were introduced, welding parameters were tested and operators trained.

Based on the experience gained with the Norcar robot welding cell, specific information about products and production was gathered. The analysis of the data provided for introducing the implementation chart of the system (based on welding/programming time ratio) and grouping the products (based on production quantity/production time). For the estimation of product suitability for production by robot welding cells in the conditions of SMEs, it is important to define the following parameters: programming time, welding time, production quantity, and program running time. This information was used for making competent decisions (Zachaaria&Aspragathos, 2005). When using robot welding, one of the most important parameters is the estimation of the programming time. Beside weld parameters, the number of movements between welds, the number of online measurements, the number of tool cleaning movements, and product complexity should be taken into account (Sarkans&Eerme, 2007). The idea of the **implementation chart** is to determine the time necessary for the robot cell to reach its full productivity. Fig. 6.7 shows the implementation chart for the Norcar-BSB Eesti Ltd robot cell. The implementation time is comparatively long, as there are over 40 products to put in use. The transition point is after 2.5 years when the main programs will be completed; as a result, the welding per cent increases rapidly. Subsequent programming time comprises new product introduction and existing program correction.

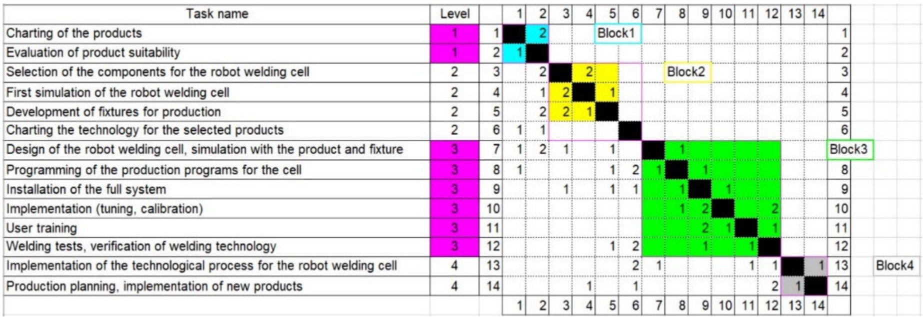


	1	2	3	4	5
🟩 programming	80	53	30	18	6
🟥 welding	20	47	70	82	94

Figure 6.7. Implementation chart (programming/welding ratio) in Norcar-BSB Eesti Ltd (Sarkans, 2012)

The effectiveness of the implementation process of the robot welding cell depends on the suitable grouping of the products welded. The basis of the comparison is the ratio of the production time/welding time. As the production quantity fluctuates, the ratio must be calculated for different years. Grouping of the products is based on four parameters: welding time, production quantity, welding length, and number of welds, as these parameters influence the grouping of the products most. Based on the data gathered from production and as a result of the analysis, the enterprise can establish the portfolio of products to be welded.

For a comprehensive overview of the implementation process, we use the DSM as a suitable tool for solving the tasks and showing the interactions between them. All the necessary actions can be carried out in a serial, parallel or coupled mode (see Fig.4.4). For completing the action-based analysis, a DSM for 14 inputs was compiled, characterizing all the necessary substantial activities during the implementation of the investigated robot welding cell (see Fig. 6.8). For clarity, the matrix processing process described in Chapters 4 and 5 is reproduced. There is no need to arrange the inputs in order as sequenced by the mathematical treatment of this matrix. All inputs must be only preliminarily numbered and therefore the numbers of the inputs must be the same on the horizontal and vertical axes. The number of the inputs is practically limitless and depends only on the complexity of the system. The strength of interaction synergy between inputs is characterized on a three-step scale: 2 – strong interaction, 1 – moderate interaction, and 0 – indifferent (blank) interaction. The primary matrix has been allocated to sequencing transformation (Cho&Eppinger, 2001). In this process, all activities are rearranged to move interaction under the diagonal that leads to the possibility to use the information of previously completed actions in a chain of activities. After the sequencing, a new order of activities is established (see Fig. 6.8). Sometimes serial and parallel activities are necessary. In some cases, the solution of the current task needs some feedback information from the later activity and those related tasks are grouped into outlined blocks.



Task name	Level		1	2	3	4	5	6	7	8	9	10	11	12	13	14		
Charting of the products	1	1	■	2			Block1										1	
Evaluation of product suitability	1	2	1	■													2	
Selection of the components for the robot welding cell	2	3		2	■	2				Block2							3	
First simulation of the robot welding cell	2	4		1	2	■	1										4	
Development of fixtures for production	2	5		2	2	1	■										5	
Charting the technology for the selected products	2	6	1	1				■									6	
Design of the robot welding cell, simulation with the product and fixture	3	7	1	2	1		1		■	1							Block3	
Programming of the production programs for the cell	3	8	1				1	2	1	■	1						8	
Installation of the full system	3	9			1		1	1		1	■	1					9	
Implementation (tuning, calibration)	3	10								1	2	■		2			10	
User training	3	11									2	1	■	1			11	
Welding tests, verification of welding technology	3	12					1	2			1		1	■			12	
Implementation of the technological process for the robot welding cell	4	13						2	1				1	1	■	1	13	Block4
Production planning, implementation of new products	4	14				1		1						2	1	■	14	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14		

Figure 6.8. Activity-based DSM for implementing the robot welding cell after sequencing (Sarkans, 2012)

The provided analysis of welding cell implementation has shown that the DSM technology is valuable for the expedient planning of the cell. The advantage of the DSM is the automated scheduling of activities granting that not one of them is missed or carried out without necessary information from previous activities.

However, it is possible to make a further step – to arrange a probability prognosis of the duration of the whole robot cell implementation process (Cho, 2001). This possibility proceeds from discrete event modelling, where the expected duration of each simulation is initially sampled using the Latin Hypercube method. All this makes it possible to compute probability distribution of lead time, taking into account the probabilistic iterations and the learning curves among tasks (see Fig. 6.9).

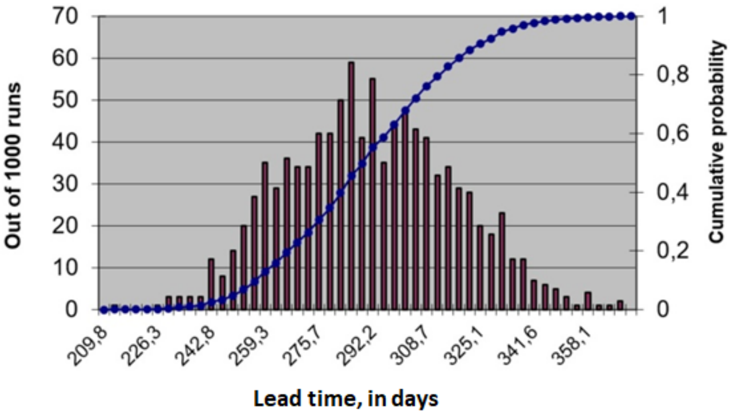


Figure 6.9. The expected duration of robot cell implementation process (Sarkans, 2012)

In summary, reaching a decision about an investment into the robot welding cell in SMEs that will bring expected profit for investors and producers is a complicated process. The alternative to a robot is always unreliable manmade welding. In mass production, decision-making is simple – robot welding is more productive and more precise than a human robot. However, this study shows how much brainwork is needed to attain positive synergy on the way to the implementation of one effective robot cell. Using the experience of the development of the first robot welding cell, two more welding cells were developed: the robot welding cell for Norrhydro Oy for welding cylinder rods and for STRAM Ltd. for welding VIP bed frames. These two cases gave evidence about the effectiveness of the proposed development approach. The expected probability durations of implementation processes were close to reality (Sarkans, 2012).

6.4. Increasing synergy in information and knowledge management

Information and knowledge management are fast growing and capacious fields of research with multiple concepts and approaches (Baddeley, 1998; Le Grand &Soto, 1999; Alpert, 2003; Tergan&Keller, 2005; Plötzner&Lowe, 2004; Sebrechts, 2005; Danserau, 2005; Burkhard, 2005). To help the readers to focus on further discussions, let us start with a short excursion into the notions used in the present context.

Data is a collection of raw symbols or non-interpreted facts without any relation to other data. **Information** is data that has obtained meaning through its interpretation in the pragmatic context and relational connection. **Knowledge** is information that has been cognitively processed and integrated into an existing human knowledge structure. The most important difference between information and knowledge is that information is outside and knowledge is inside the grip of the brain. **Visualizations of information and knowledge** play an important role as visualizations capitalize on several characteristic features of the human cognitive processing system. **Information visualization** is the term used to signify a representational mode (as opposed to verbal descriptions of subject-matter content) used to illustrate in a visual-spatial manner, for example, objects, dynamic systems, events, processes, and procedures. However, computer scientists define the term in a more narrow sense and refer to it as "the use of computer-supported, interactive, visual representation of abstract non-physically based data to amplify cognition" (Card et al., 1999). For **knowledge visualization**, spatial strategies are required to help individuals in acquiring, storing, restructuring, communicating, and utilizing knowledge and knowledge resources, as well as overcoming capacity limitations of individual working memory (Holley&Dansereau, 1984; Tergan, 2005; Ware, 2005).

In our research, we focus on introducing the synergy-based approach to interpreting information and knowledge visualization addressed to the fields of expedient modularization. Our focus is on: the design of multi-agent production processes and product modularization in perspective to build a knowledge-base for technical education (Scaife&Rogers, 1996). It is intelligible that information and knowledge visualization in the conditions of the limited resources (as in SMEs) is to be organized in such a way that it may be accessed easily and comprehensively focused on the attaining of synergistic thinking. Synergy effects may result with respect to the user-centredness of visualizations (Larkin&Simon, 1987; Carr, 1999; Cox, 1999; Mayer, 2001; Sebrechts, 2005). It is important to discriminate between two kinds of approaches: dealing with visualizations of knowledge and information to speed up learning and instruction on the one hand and visualizations of knowledge-oriented information organization to foster information use on the other hand (Jonassen, 1991; Neumann et al., 2005; Siemens, 2005).

Let us now turn from the theoretical and methodological treatment of information and knowledge back to their application. It is obvious that at planning any product and production cell, the information extracted from these needs has to be visualized. Parallel to this, a suitable model for information about expedient modularity has to be proposed.

For the proposed modularization information model, it seems to be best to choose a **layered structure**. In this case, a different level of modularization information is easy to insert (interfaces – number, types, strengths; functional modules; interface drivers). The proposed module informational room in Fig. 6.10 shows three approaches and their relative position in this room:

- functional decomposition (1) – functional modules are placed into the start of the PD process where the abstraction level is high;
- MIM and drivers (2) are placed in the middle of the PD process. The product is now less abstract and
- metrics (3) are placed at the end of the PD process where the product is on a more concrete level.

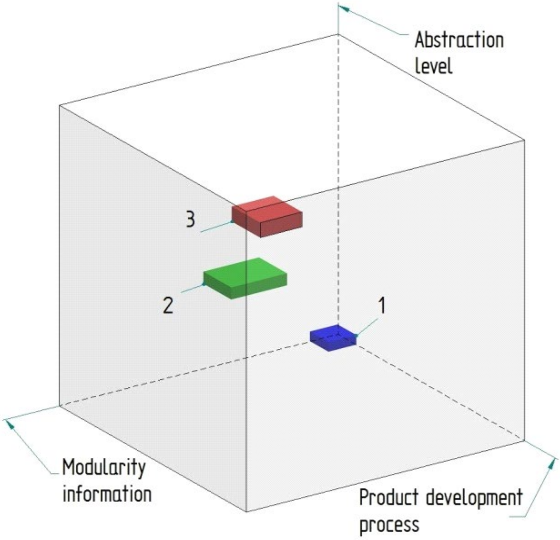
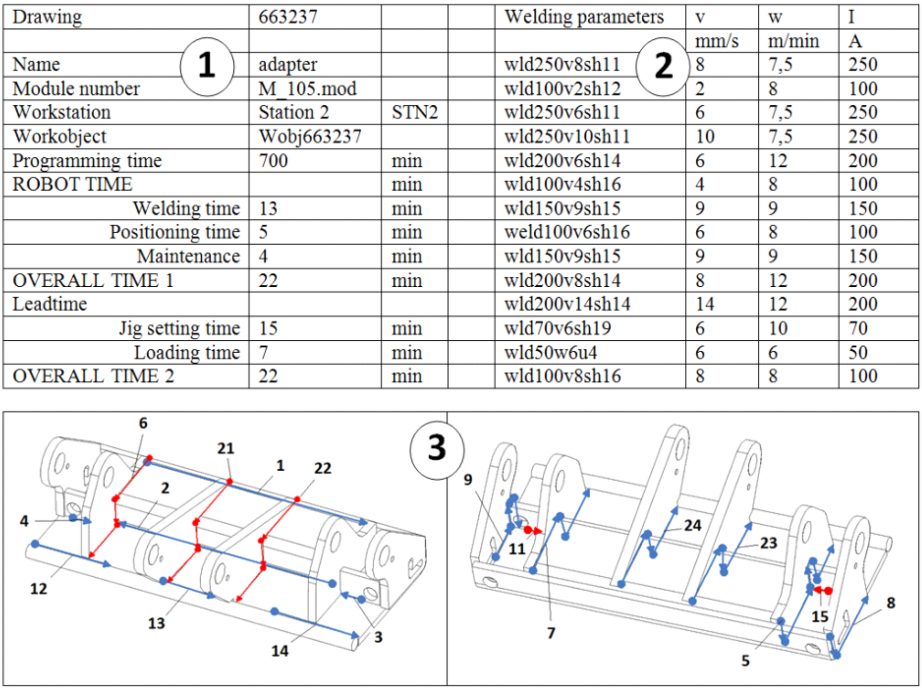


Figure 6.10. Module informational model developed from TDD model (based on Andreasen, 1993)

The proposed information model has a layered structure and necessary information (knowledge) can be extracted during system implementation at different stages of the process.

Product and production process analysis layer. Here it is better to present the results of the analysis in the form of a technology chart (see Fig 6.11). This layer includes information about modules, virtual reality models, agents, database modules. In this layer, the data about product welding technology, knowledge about welding sequence and calculation of production time are included (Gultekin et al., 2009). The analysis results are used to select a suitable product for a robot welding cell.



Drawing	663237			Welding parameters	v	w	I
					mm/s	m/min	A
Name	adapter			wld250v8sh11	8	7,5	250
Module number	M_105.mod			wld100v2sh12	2	8	100
Workstation	Station 2	STN2		wld250v6sh11	6	7,5	250
Workobject	Wobj663237			wld250v10sh11	10	7,5	250
Programming time	700	min		wld200v6sh14	6	12	200
ROBOT TIME		min		wld100v4sh16	4	8	100
Welding time	13	min		wld150v9sh15	9	9	150
Positioning time	5	min		weld100v6sh16	6	8	100
Maintenance	4	min		wld150v9sh15	9	9	150
OVERALL TIME 1	22	min		wld200v8sh14	8	12	200
Leadtime				wld200v14sh14	14	12	200
Jig setting time	15	min		wld70v6sh19	6	10	70
Loading time	7	min		wld50w6u4	6	6	50
OVERALL TIME 2	22	min		wld100v8sh16	8	8	100

Figure 6.11. Technology chart for the robot-welding cell (Sarkans, 2012)
Area 1 – program parameters; area 2 – welding parameters; area 3 – welding directions and sequence

System configuration layer. Based on the technology analysis, the system hardware is selected here. The virtual system configuration can be compiled as shown in Fig. 6.12. This layer includes information about modules, virtual reality models, agents, and the functional diagram. This enables the right components to be selected for the robot welding cell based on the analysis of the products. During this process, several cell concepts may be worked out.

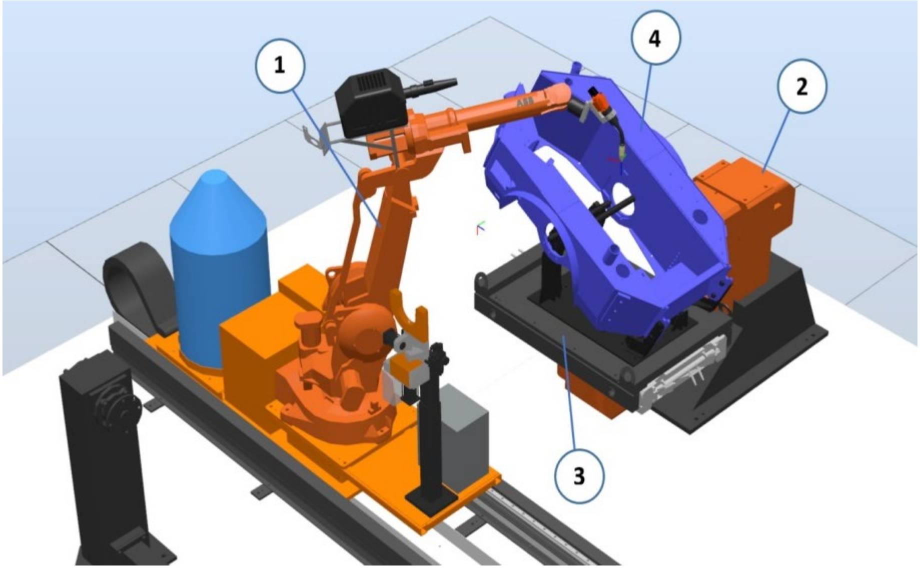


Figure 6.12. Virtual environment for system and product testing (Sarkans, 2012)
1 – robot; 2 – product manipulator; 3 – jig; 4 – product

In the **system simulation layer**, the feasibility of the system and the product by using virtual reality software (CAD; RobotStudio) (Dolinsky et al., 2007; Gonzales-Galvan et al., 2008) is tested. This simulation is usually provided out of enterprise before the decision about buying/licensing the hardware. This layer includes information about modules, virtual reality models, agents, functional diagram, and technological modules. Based on the approved concept of the robot welding cell, the final concept is fully simulated, including all work movements and reachability check.

Facility layer – this layer is bound to the real system installation in the factory. Usually, here the CAD and virtual reality information must be updated. This layer includes information about agents and functional diagrams. The layer can also be treated as a stage of the previous system simulation or as a part of the next installation layer.

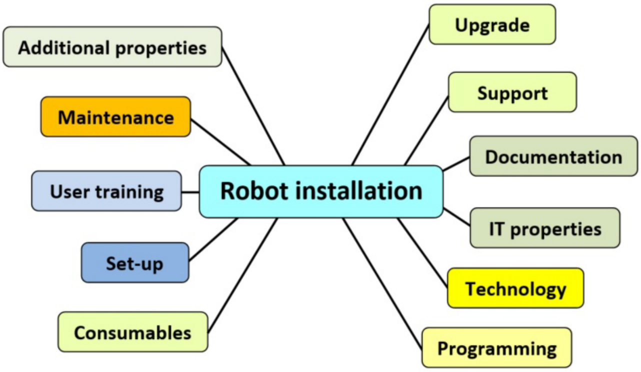


Figure 6.13. System installation layer for the robot-welding cell (Sarkans, 2012)

System installation layer. This layer consists of all information and policies for the support of system installation in the real factory. Figure 6.13 shows the topics provided during installation. This layer is indisputably the most extensive and many-sided. However, due to the close interaction of its activities it is not appropriate to divide its components into different sub-layers.

Jig layer. Principally, here it is necessary to connect the system and the product with each other. This layer includes information about modules, virtual reality models, and agents. This layer is not simple as the jig must be designed to be multifunctional and easily adaptable to future products.

Programming layer. This layer includes all program modules, welding positions, and additional modules.

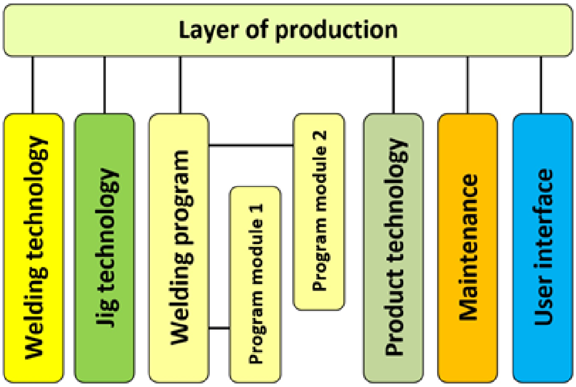


Figure 6.14. Information included in the production layer (Sarkans, 2012)

Layer of production. Figure 6.14 shows the main issues concerning this layer, including information about policies, modules, and agents.

In the conditions of SMEs (at limited resources), defining the layers of the visualization of information (knowledge) is a useful tool to present a complex system. For sharing information and decisions between the layers, it is appropriate to form the virtual info-room, which acts as a carrier of the information (knowledge) about the system (see Fig. 6.15). First, the information extracted from the system layers has to be clearly arranged and each layer can be defined with a distinct detail level. Also, it is possible to move the modules between these layers and update them with additional information (knowledge). By having a layered structure, it is easier to grasp system properties and movements between the layers to understand interconnections between the different parts of the system.

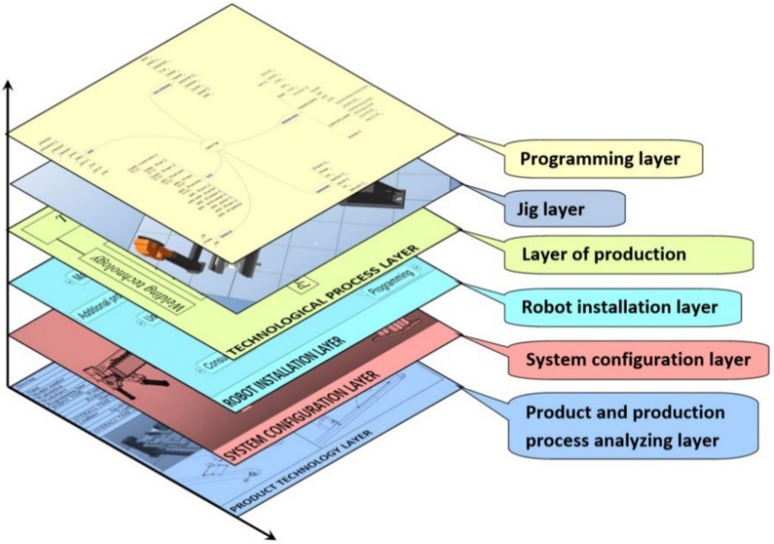


Figure 6.15. Layered virtual info-room for complex system implementation (Sarkans, 2012)

By dividing the complex system into layers and by connecting layers with modules, it is possible to use software agents, which enable communication between the layers. The subsequent model is shown in Fig 6.16 where modules share information between layers and agents share decisions. Decisions by the agents can be made based on several criteria, which are defined in the layer. For example, the decision about product suitability for robot welding is a multi-criterion problem where product dimensions, welding length, and number of welds play an important role in decision-making.

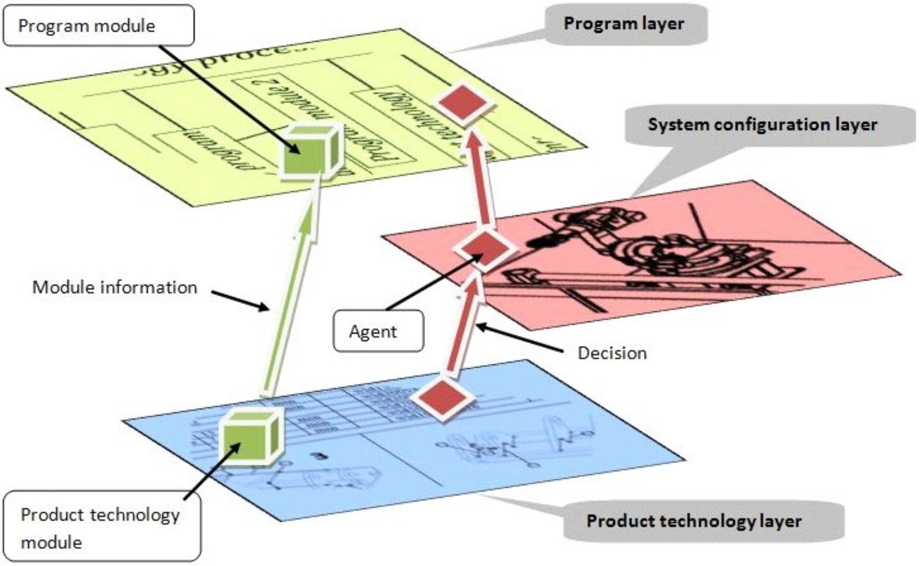


Figure 6.16. Sharing information between modules and decisions between agents (Sarkans, 2012)

It is possible to use the virtual layered module for the development of the expert system for the design of a new robot welding cell. The purpose of this expert system is to support the selection of the components of the robot welding cell (robot, positioner, welding power source, and jig), to describe the welding technology of products for the selection of the welding jig and for economic calculations (price of welding, estimated price of robot welding cell, jig price, and payback time).

In summary, the implementation of a robot welding cell on the information and knowledge level is a complex process. To reach positive synergy, appropriate modularization and integration of all activities is necessary. It is possible to evaluate the share of positive synergy by the level of profitability of an investment into a robot cell. It is impossible to empower positive synergy and gain success without taking care of staff competence. The layering approach described above has been tested successfully during the implementation of the robot welding cells in three SMEs: Norcar-BSB Eesti Ltd, Norrhydro OY, and STRAM Ltd. All the values of the synergy-based thinking described above in Chapters 2-5 have proved to be valid for the context of the present chapter of the book.

7. CHAOS CONTROL IN MULTI-AGENT HIERARCHICAL TEAMWORK

R. Källo, M. Eerme, V. Reedik

7.1. Constraints and special features in factory process automation

In today's reality, factory process automation systems have become increasingly complex and the amount of data and variables circulating in these systems has grown enormously. Technologies, including wireless networks, fieldbus systems, optimization algorithms, analytics solutions, cloud computing, and asset management systems, boost the efficiency of factory process control systems. 4th generation Industrial Revolution (Industry 4.0) is based on the Cyber-Physical Systems (CPS), the transformative technology connecting physical assets to computational technology (Lee et al., 2014). All the industrial devices would be connected to the Industrial Internet of Things (IIoT) and have intelligence built into them to communicate directly with other devices and systems (Benson, 1997). As a result, the automation system design becomes complicated and costly and the reliability and quality problems arise. At the same time, every specific factory needs a specific process automation system to be configured on the basis of some universal system (Jämsä-Jounela, 2007; Patrick& Fardo, 2009).

Resulting from the situation described above, a new wave of research into the role of human shortcomings emerged at the beginning of the present century (Blessing, 2003; Eppinger, 1997). The management and improvement of skills and competences in a decentralized organization is becoming increasingly important (Jämsä-Jounela, 2007). Increasing complexity of knowledge and information has created the need of their structuring and ergonomic visualization (Tergan&Keller, 2005). Analysis of testing and start-up data of real process automation systems shows that negative synergy due to human shortcomings can increase the start-up costs of the factories by up to 5–10%. Finding and eliminating the consequences of human shortcomings takes much time and causes delays on factory start-up.

New automation systems must be modelled to have more information about the physical processes available for the process control systems from the beginning (Isermann, 2011). For this purpose, MPC (Model Predictive Control) models are being integrated to DCS (Distributed Control System) control logic to enable continuous optimization of the process. The focus in the present research is on the process automation systems. System-wise there are not many different philosophies of process control systems to use: DCS (Distributed Control System), PLC (Programmable Logic Controller), HMI (Human-Machine

Interface), SCADA (Supervisory Control and Data Acquisition) or Hybrid Controller (see Fig. 7.1).

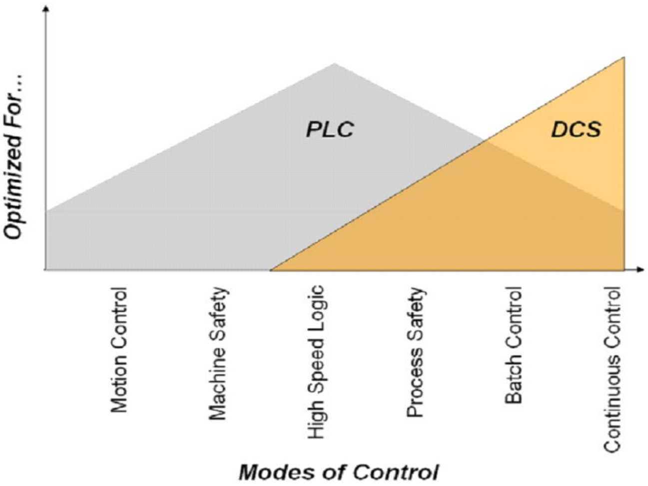


Figure 7.1. Comparison of control modes (Shaikh, 2009)

The process control system (see also Chapter 3) is one of the most important factors during factory automation (Thane, 1966). System reliability is highly dependent on the reliability of the components used, interactions between the units, data communication and software. Reliability in our case can be defined as a probability of failure-free operation of a system for a certain period of time in specific environmental conditions (Lin, 2012). As one unreliable element can disable the whole system, the critical components must be evaluated or duplicated for reliability before integrating them to the automated process control system.

With the increasing complexity of design in the production plant control systems, the probability of human shortcomings is increasing due to the growing number of communication activities and component sophistication. The key figures in systems engineering, design and commissioning are the human beings with their cultural, educational and technical backgrounds and organizational behaviour. As a project is not continuous in duration, a team with certain tasks and responsibilities formed is a temporary organization by nature (Samad et al., 2007). Due to the temporary nature, the hierarchical teamwork system of the project is more dynamic and involves more uncertainty in a discontinuous environment (Huemann et al., 2007). The project management philosophy has changed from technical to human project management (Turner&Müller, 2003) or more specifically, team management (Delisle, 2004; Lorsch&Lawrence, 1972). So, the present study of negative synergy in teamwork is in every way necessary.

To understand the process of project implementation of a factory process automation system, an overview of the project schedule is presented in Fig. 7.2. Chronologically, the process of industrial plant automation system design starts from the drafting of the general concept of factory operational principles, followed by particularizing specific requirements and system architecture for system configuration purposes (EVS-EN 62381:2012 2012). Next, detailed design activities are composed, followed by the implementation of system and application software and the Factory Acceptance Test (FAT). After a successful FAT, the automation system is verified during the commissioning phase in the factory and the project is handed over to operation and maintenance.

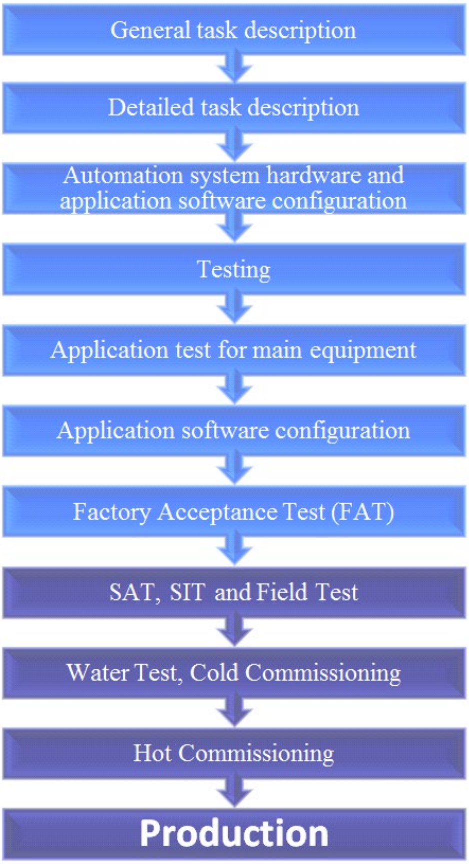


Figure 7.2. Chronological implementation of an industrial process automation project (Källo, 2016)

Recommended by the Industry 4.0 program, it is possible to join all factory operation into one smart factory system (Stock&Seliger, 2016), including process control, business operations, safety systems, power management, instrumentation supervision, heating and ventilation, access control, lighting, security cameras, service solutions, and product quality systems. However, occasionally, separate systems for the above purposes have been found more reasonable from the financial, operational or security point of view.

7.2. Chaotic coherent collective dynamics in teamwork

Traditional approach to a temporary hierarchical project organization is based on the teams formed by commercial sub-projects and binding of the actions together by an owner's responsible team activities (Sharma, 2011). A rational deterministic project team structure is presented in Fig. 7.3, where the team for certain sub-projects is marked with different colours that represent different companies involved in the project organization. Effective implementation of project tasks by the team members requires planning of information flows between the team members and the different companies involved.

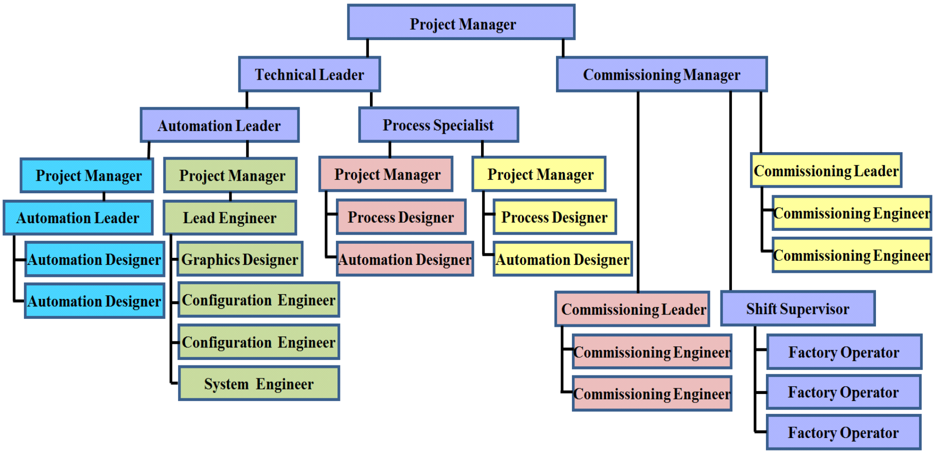


Figure 7.3. Organization chart of a traditional industrial process automation team (Källo, 2016)

The process of hierarchical transfer of information from one team to another in scheduled time is very sensitive to tainted information (Mikhailov et al., 1991; Hilborn, 2001). In such multi-agent distributed artificial intelligent systems, agents' decisions depend on those made by the agents upper in the information flow. If the agents use tainted on imperfect information, they tend to make poor decisions. In summary, it leads to the chaotic behaviour of downwards agents and downgrading of the performance of the whole system (Ivancevic&Ivancevic, 2008). As a result, human shortcomings may cause real chaos (see Fig. 7.4) in the control system design and commissioning, making the whole system complicated and nonlinear (Eppinger&Browning, 2012). The industrial process automation project is also a highly interactive social process involving many people and teams for working with several sub-disciplines making millions of coupled decisions (Eppinger&Salminen, 2001, Tang et al., 2010, Källo et al., 2013; Kreimeyer&Lindemann, 2011).

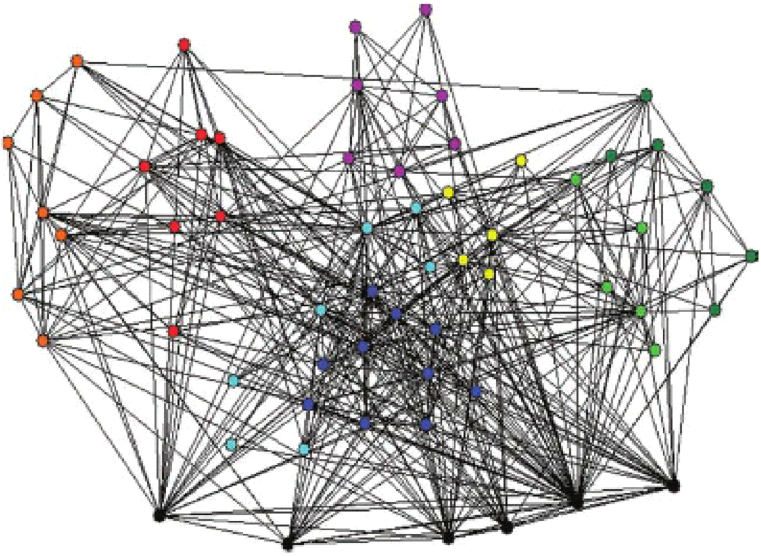


Figure 7.4. Communication network node-link diagram as visualization of a chaotic system (Eppinger&Browning, 2012)

First, it is necessary to determine the position of the current research on the complex research field of chaos control, stretching from cells to societies (Mikhailov&Calenbuhr, 2002). On the one hand, the generic mechanism of growing chaotic behaviour in the framework of industrial control system project design and commissioning belongs to the field of chaotic dynamics of binary systems since all the decisions in these systems result from neural networks activities (Botina et al., 1995). At the same time, realization of these decisions is similar to spatio-temporal chaotic dynamics, where the hierarchical system is lacking long-time and large distance coherence in spite of organized local behaviour (Manneville, 2005). Because of human faults and mistakes, the chaotic trajectories must be corrected by iterations and the rework and the chaos control system must have the feedback nature. As the third factor, the task has the stochastic or random nature, as human shortcomings are predictable only by statistical data collected during the realization of industrial process control projects. Thus, the bundle of initial conditions makes it complicated to position the present research, but it is clear that it belongs to the category of the hierarchical model of complex coherent actions (Mikhailov&Calenbuhr, 2002).

Chaos is a complex behaviour of a simple, well-behaved deterministic system, where its aperiodic performance, depending on initial conditions, makes prediction of system behaviour impossible (Strogatz, 1994). Interactions between agents in complex distributed systems are forming many stationary and time-dependent patterns. The chaotic patterns are uncorrelated and consist of many irregular elements and can be influenced by internal or external noise (Mikhailov et al., 1991). Chaos is normally an undesirable behaviour of the system, which should be avoided or controlled if its avoiding is impossible. Typically, chaos should be decreased to minimum or suppressed (Cheng& Dong, 1998; Schöll&Schuster, 2008).

A basic nature of a system's chaotic behaviour is its critical dependence on the initial conditions. Due to that and the fact that initial conditions are never known exactly, the chaotic systems behaviour is naturally unpredictable. The trajectory predicted from initial conditions may differ from the real trajectory exponentially in the course of time (Ivancevic&Ivancevic, 2008). Chaos control is possible by introducing stabilizing perturbations to the system, which move the process trajectory closer to the desired one. Small perturbation can cause a significant change in the course of time if introduced at the correct time and in an appropriate place (Boccaletti et al., 2000); this so-called "butterfly effect" seems to be the most promising concept also for the present research.

E. Ott, C. Grebogi and J.A. Yorke introduced the idea of chaos control called OGY in 1990 (Ott et al., 1990; Deng et al., 1995). This method of chaos control is stabilizing unstable periodic orbits by applying carefully selected perturbations to the system to create desired system dynamics. As a modification of OGY, the proportional perturbations feedback (PPF) control was introduced to fix the timing of external agitators. This was stabilizing the trajectories to periodic instead of irregular spikes, seen in the uncontrolled system. This method is known as blind chaos control (Kaplan, 2000) and seems to be a valuable research direction.

The stochastic nature of the hierarchical process needs some modelling technology for the evaluation of time-dependent processes. In the modelling of any system, first, the problem of treatment of the agent with its complexity of relations and stochasticity emerges. So the agent in a teamwork system can be treated as a discrete automaton with stochastic dynamics (Mikhailov&Calenbuhr, 2002). It is possible to define this automaton with a limited repertoire of responses as they act in their working process (not fully expressing their complexity). Thus, it is possible to model the interaction and behaviour of an active agent as a dynamic and evolutionary network participant in the class of hierarchical organizations. This opens up the way to describe the “strength“ of agents’ interactions and to take into account the synergy of these relations (Eppinger, 1997, Kaljas, 2005, Hindreus, 2009).

7.3. Study of human shortcomings in factory process automation projects

The backbone of this research is an unique database covering the shortcomings in the preparation, design, commissioning, and start-up of the process automation systems of new or renovated production plants, which includes 26 factories from all over the world collected for about 17 years (Källo, 2016). Such a unique database gives evidence of authenticity and applicability of this empirical research results. The factories remain unidentified due to sensitiveness of the data.

From the production point of view, these factories belong to five main groups:

4 pulp mills,
11 paper mills,
4 power plants,
6 chemical and petrochemical plants,
1 steel mill.

The database contains the analysis of reasons, solutions and labour-consuming weight of the faults, mistakes and bad decisions discovered during the project implementation. In the first analysis of the database carried out up to year 2006, human shortcomings were classified as used in section 3.2 (Källo& Reedik, 2001). For later research, an advanced and more detailed database for the period 2006–2015 was compiled. Figure 7.5 shows an advanced classification of human shortcomings, caused by the change of the environment and operating conditions of the human beings in the meantime. Therefore, strategic miscalculations **S** were separated and additional criteria were provided for omitted procedures **F3** and systems integration disability **M3**. At the same time, it simplifies the utilization of corrective actions for blocking and hindering the difficulties during the project implementation period. Technical problems of reliability were handled as a separate category.

Figure 7.5. Advanced classification of human shortcomings (Källo, 2016)

Faults **F** are the dominating shortcomings in the process automation development process. Therefore, reducing human faults is a key factor of the quality, reliability and system performance improvement as well as the time and costs reduction during the project implementation.

There are three main categories of human faults with subcategories as follows:

F1 – Communication faults:

- Incompletely collected initial data;
- New ideas emerging during the whole implementation process;
- Misunderstandings in communication between work teams and individuals involved in teamwork.

F2 – Negligence:

- Faults of copying and creation of the system software;
- Faults of connecting the equipment to the system;
- Insufficiently considered decisions.

F3 – Omitted procedures:

- Faults of handing over initial information at proper time, extent and quality;
- Leaving important part of the work undone;
- Wrong scheduling of the work packages;
- Faults caused by information overflow.

Mistakes **M** have a more complicated nature and thus are more difficult to avoid; however, it is essential to take measures to reduce their amount to achieve better cost- and time-effectiveness.

In the classification, the mistakes category is divided into three subcategories for a more precise specification of the nature of shortcomings:

M1 – Lack of competence:

- Lack of single team member competence;
- Insufficient support from other team members;
- Incomplete initial information about team members' competences and thus unreasonable expectation in their allocation for task solution.

M2 – Impossibility of prediction of the variables:

- Unavailable competence in a specific area;
- Evaluation of the variables possible only during testing.

M3 – Systems integration disability:

- System hardware is on the different level of development;
- Software incompatibility with a different release of software packages.

Strategic miscalculations **S** are more cost-consuming shortcomings during the design and commissioning. These miscalculations are usually made before the work has started and it is impossible to influence them during the design or commissioning.

There are two subcategories of strategic miscalculation for the analysis of their nature:

S1 – Contestable decisions:

- In large work packages, insufficient attention is paid to its details;
- Contracts for work packages are sequenced incorrectly;
- Outsourcing the documentation is not detailed enough, which leads to a temptation to sell additional materials or services by the supplier later, in the course of the project.

S2 – Contribution underrate:

- Problems with work plan scheduling;
- Overestimated evaluation of the efficiency of contribution;
- Unclear extent of needed work efforts.

The last category is technical problems **T,** which involve classical reliability issues.

The shortcomings database contains information about how the shortcomings were discovered and therefore it may describe its symptoms rather than the real nature of the shortcoming. Therefore, a systematic analysis of the situation at the time of occurrence of a shortcoming is necessary to reveal its real reason.

The main hindering process for human shortcomings is the Factory Acceptance Test (FAT) and commissioning tests. Fig. 7.6 shows the quantitative share of certain shortcomings found during the FAT. FAT is performed to find all the possible problems occurring during the design phase and those found at the simulation of the automation system. From the shortcomings discovered during that period, faults **F** form more than half of all the problems. These are usually clarified and fixed during the FAT; however, they may hinder effective work during tests and may lead to a rush at the end of FAT. Communication faults **F1** made during the project design phase are caused by poor communication where all necessary information is not transferred properly between the teams, which leads to solutions based on predictions. Items not discussed belong also here when different team members understand the documentation in different ways. Negligence faults **F2** can be caused by copying the documents and not paying sufficient attention to adapting the copied solutions to a new use. It also covers the design or configuration work done in a hurry, not paying attention to all the details. Omitted procedures **F3** cause the largest loss in time and resources, as insufficient initial information leads to additional rework. The common faults belonging to category **F3** is missing information in documents or not meeting the document delivery deadlines.

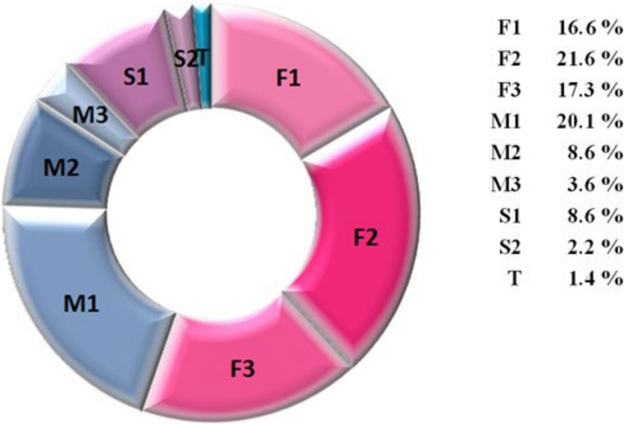


Figure 7.6. Statistics of human shortcomings discovered during the FAT test (Källo, 2016). See the classification scheme in Fig. 7.5.

Mistakes caused by lack of competence **M1** include insufficient personal competence during the project work. The missing competence can usually be found inside the team or company involved in the project. The mistakes of type **M2 -** impossibility of prediction of the variables - are more difficult to avoid and fix due to unavailable competence in this specific area or awareness that a specific kind of competence is required. The need for necessary modifications may arise during the testing of the sub-processes of specific application software. Solution of these problems requires a high level of overall technical competence. System integration disability problems **M3** are usually related to different levels of development in soft- or hardware. The development is everlasting and does not consider always all the areas of possible use of a specific item.

Share of strategic miscalculations **S** is rather small compared to previous categories but their financial impact on the whole project can be significantly higher. Contestable decisions **S1** usually occur when work packages for specific teams are relatively large and a temptation arises to save resources in smaller sub-items. **S2** type of contribution underrate shortcomings arise due to the market pressure and industrial investments dynamics, which leads to inability of scheduling the work according to specific project needs. Inefficient scheduling or delays in some projects may lead to a need to work with several concurrent projects at the same time. The percentage of technical errors **T** is rather low, consisting mainly of automation system hardware failures.

Commissioning is the last scene to find problems by the automation system testing with real process equipment, in which an attempt is made to arouse all possible scenarios of the process behaviour. During the commissioning, the distribution of shortcomings is slightly different from FAT problems, and reasons of this vary (see Fig. 7.7). The largest group of shortcomings is still faults **F**, however, not as dominating as in the statistics of the FAT test. The nature of faults is different too and the largest share is taken by communication faults **F1.** The areas of concern are the affiliation points between the mechanical complexes, equipment packages or the automation systems. As new teams are introduced to the project, the documentation and information exchange becomes more important and is a new area of faults. A substantial group of discovered faults is negligence **F2** when errors made during installation, calibration and configuration of field instruments are discovered. **F3** type of faults in the commissioning stage can be described as a designer's inability to consider systematically the production processes. In some cases, omitted procedures **F3** can indicate the omissions during Hazard and Operability study (HAZOP) and Safety Integrity Level (SIL) assessment.

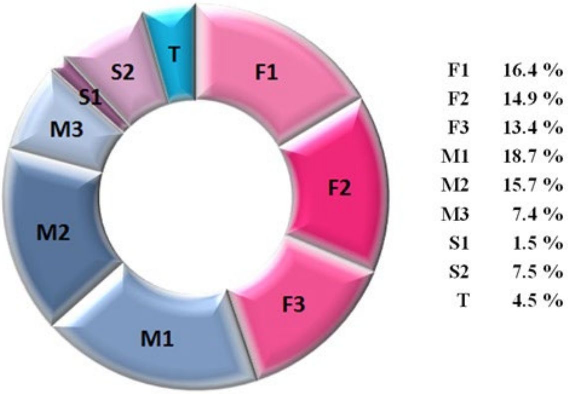


Figure 7.7. Statistics of shortcomings of the process automation system discovered during the commissioning in the factory (Källo, 2016). For the classification scheme see Fig. 7.5.

The second and a smaller part of the discovered shortcomings are mistakes **M** where the largest share is lack of competence **M1.** As the systems and subsystems commonly used are complicated, deep knowledge and experience with them are increasingly important. Sometimes the overall process knowledge proves to be insufficient. A usual shortcoming is lack of experience in integrating different types of process equipment mechanically and logically. Sometimes the systems delivered to the factory by different suppliers are in different levels of development and their functionality with other systems is not tested carefully enough. Also, behaviour of equipment combined into the process system can differ from the designed properties, causing modifications in initial information packages. In this case, problems are classified as **M2**, as impossibility of predicting the variables. This category of mistakes is increasing in today's conditions of rapid advance of technologies. Problems of competiveness or disability of systems integration form a majority of mistakes **M3.**

Strategic miscalculations group **S** is slightly smaller than during the FAT, but are important as the resources and time spent for their removal are relatively large. Because of the financial pressure, the installation and commissioning contractors try to take a package as large as possible to survive in a dynamically changing market. But their knowledge and experience may not be enough for the fast-developing field of process automation.

Technical shortcomings **T** in the commissioning phase are mainly caused by the damage on transportation or handling, unsuitability of equipment or faulty communication interfaces between the subsystems.

The distribution of shortcomings is quite close for a majority of the projects. In summary, to remove the problems during the project covering all teams in the project, on average between 1500 and 3000 working hours of additional working time is required. Additional losses result from a later start of production and non-completion of contractual obligations towards customers. Finally, the influence of human shortcomings on the effectiveness of the project depends highly on the competence of the project teams and the complexity of the tasks. As any of the shortcomings may be leading to chaotic behaviour of the socio-technical system, it is extremely important to keep the whole process under continuous control (Källo et al., 2014).

7.4. Preventive chaos control in hierarchical system implementation

This section is focused on the synergy-based chaos control in a complex hierarchical teamwork. In his doctoral research, Rommi Källo examined that area, which is a logical follow-up to the research described in the chapters above (Källo, 2016). This doctoral research is based on the databases collected by the author during his work as project manager in real factory automated process project realizations. The main problem here is a reality that human shortcomings spreading through multi-agent information channels can give rise to a chaotic behaviour of the agents participating in the whole design and commissioning process. To improve the situation, it is necessary to create an effective chaos control system for well-timed hindering and blocking the spreading of human shortcomings in this multi-agent hierarchical system.

To find proper tools for analysing the complexity of project implementation, it is necessary to describe the structure of this hierarchical socio-technical system and find ways to decompose it to manageable units (Zulch, 2014). Human shortcomings in communication, as random processes in the project organization, are causing certain chaotic behaviour of the whole hierarchical structure (see section 7.2). These processes can be described by the statistical probability distribution of random events or sequences of events and trajectories. Discrete random processes can be analysed by involving the probabilistic automata, where the system's state is described by some continuous characteristics vitiating in time and these can be handled by the continuous random processes theory. To determine the probability of a specific trajectory, the probability density function can be used (Mikhailov&Loskutov, 1991).

The key of efficient communication procedures lies usually in the hands of project and team managers, but other team members also influence the realization of communication procedures. In the search for a suitable tool for describing human relations and grouping communication procedures on the basis of their cooperation capabilities, the network modelling technique of the Design Structure Matrix (DSM) has proved to be most suitable (Eppinger et al., 1994).

The DSM technology allows us to develop, design, manage and visualize the complex relations between all team members. The powerful analysis package includes the graph theory, matrix mathematics and some specialized DSM methods (Eppinger&Browning, 2012). DSM has been used for a long period to manage complex engineering projects, handle components and their interactions as architecture of organization or structure, communication, activities, relationships, and information flows. The present research team has already successfully used DSM for empowering synergy in office machine design, at light fitting design and production, control system design for production equipment, as well as in quality assurance systems certification (see Chapters 3-6).

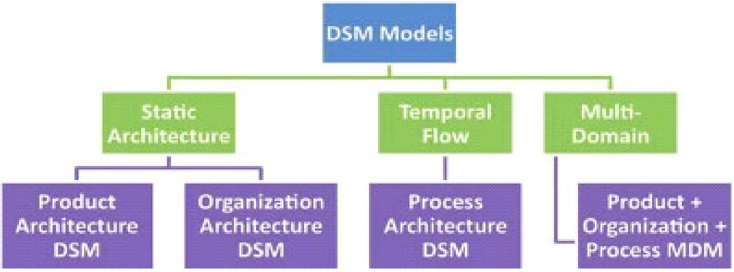
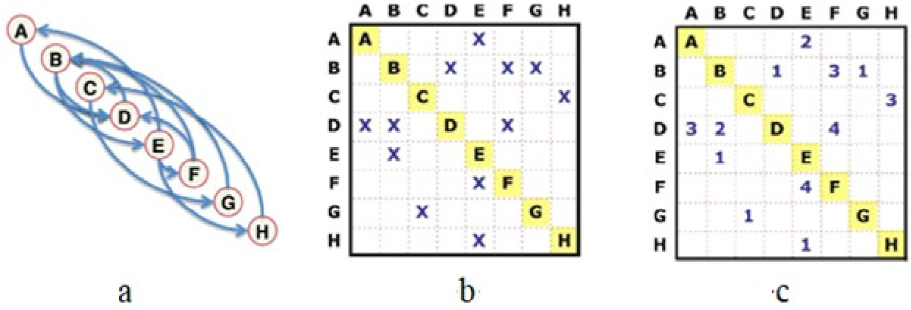


Figure 7.8. The advanced classification of DSM models (Eppinger&Browning, 2012)

When analysing the hierarchical structures, some additional circumstances have to be emphasized. The DSM models are classified into four different types (see Fig. 7.8). DSM uses a five-step approach to the system modelling and analysis – decomposing to break the system into elements, identifying to mark the relationships, analysing to rearrange the structure, displaying to represent the model graphically, and improving to take the steps towards effective communication scheduling (Eppinger&Browning, 2012). In our case, the Organizational Architecture DSM is the most important model that allows organizing the communication flows between the agents and finding possible iteration loops.

A major advantage of using DSM is the graphical visualization of the square matrix structure, which makes the system architecture easily readable. The DSM can be (see Fig. 7.9) of a binary type, indicating only if the interaction is present or not, but can be extended with additional attributes indicating the type, strength, importance or impact of interactions (Eppinger&Browning, 2012). Partitioning by the Boolean matrix operation based on the graph theory and developed by Warfield (Warfield, 1973) allows for finding the optimal communication schedules and groups that identify the dependencies in the matrix structure (Cho, 2001).



	A	B	C	D	E	F	G	H
A	A				X			
B		B		X		X	X	
C			C					X
D	X	X		D		X		
E		X			E			
F					X	F		
G			X				G	
H					X			H

	A	B	C	D	E	F	G	H
A	A				2			
B		B		1		3	1	
C			C					3
D	3	2		D		4		
E		1			E			
F					4	F		
G			1				G	
H					1			H

Figure 7.9. Representation of the DSM system (Eppinger&Browning, 2012)
a – diagram; b – binary; c – numerical form

The tools above are essential when looking for an approach to the problems by help of synergy-based thinking. The main purpose of the synergy-based approach to multi-agent processes is to find a management philosophy of highlighting and amplifying positive synergy and preventing discrepancies caused by negative synergy in the teamwork processes. The system can be extended by introducing the time scale to the project implementation layout and then decomposing it to manageable subsystems. By help of the DSM technology and discrete event modelling, it seems possible to find the areas of tracking and hindering the faults and mistakes and work out the methods for minimizing the difficulties during project implementation.

In the context of the present research, the quantitative evaluation of synergy moves to the fore and it is reasonable to transform Fig. 1.1 into a new form. In Fig.7.10, the quantitative characteristics of positive and negative synergy are addressed to the work and rework amount. The previous percentage scale is used where 0 represents a synergy-free system although it is difficult to imagine any engineering project with any sign of positive synergy. It should be reminded here that +100% means reaching maximum synergy, when everything is squeezed out of the communication and integration processes. Negative synergy -100% marks the catastrophe situation where the whole process has failed and further activities are stopped.

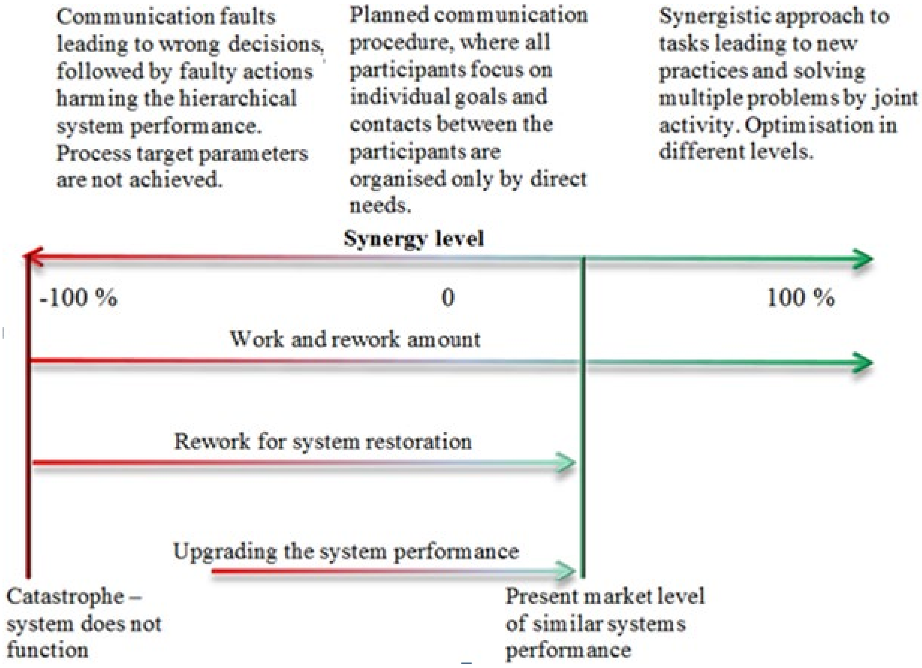


Figure 7.10. Positive and negative synergy relation to the work amount (Källo, 2016)

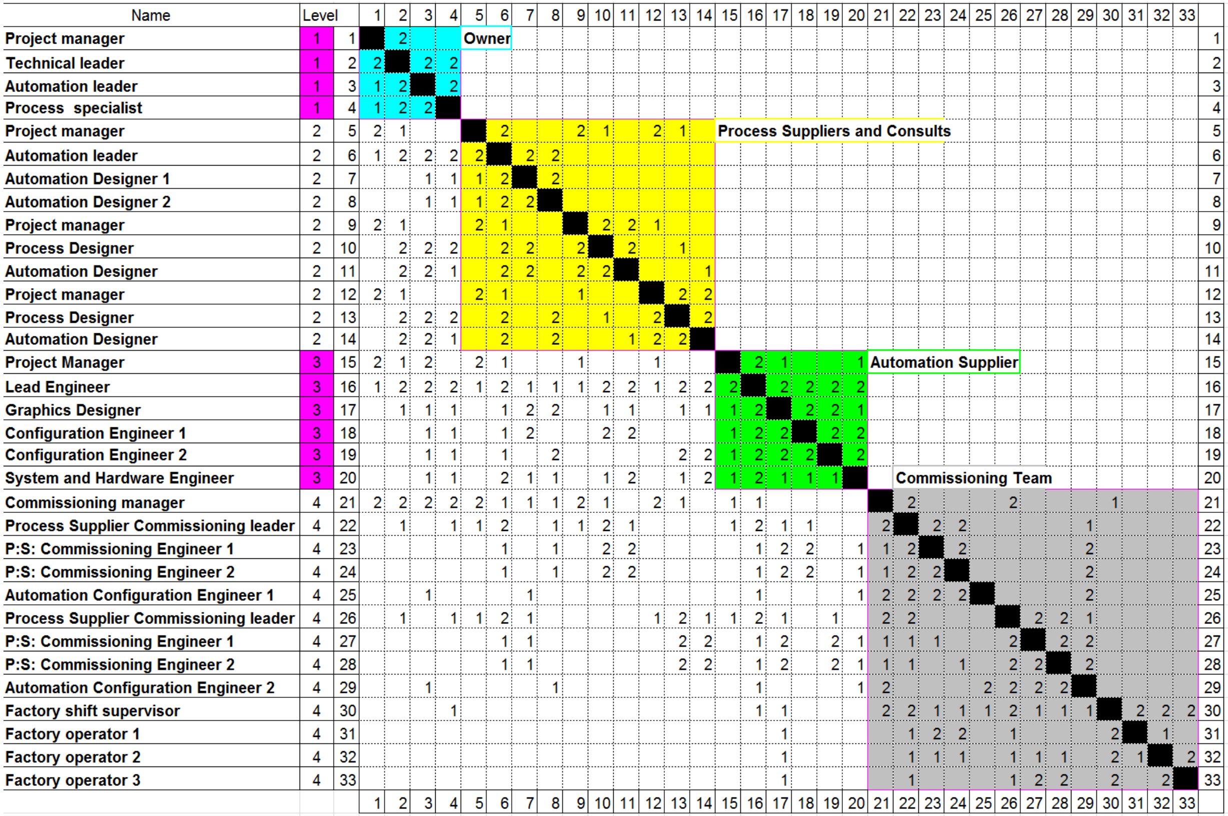
The research plan presented can be described in two action levels, which may be specified as a preventive and an active level. The first level activity is pushed from behind to avoid chaos genesis and dissemination during the design and commissioning of the project implementation of an industrial process automation system. It is inevitable to outline the detailed overview of all information flows and cooperation tasks in the project with a proposal of weights of collaboration intensity on the project description level. The only real way to predict human shortcomings is the statistical evaluation of their occurrence probability on the basis of empirical research (see section 7.3). To understand the reasons of chaos, it is necessary to identify the source of chaos and map possible trajectories of human shortcomings spreading in the hierarchical teamwork system.

The second level activities for fighting with the chaos include forming temporary meta-structures for smooth project implementation and building up the online system of continuous tracking and appropriate reaction to human-related faults and mistakes during the project implementation. Here it is necessary to focus on the transfer of timing to the project implementation. The statistically estimated duration of the project implementation is based on the time distribution and communication pattern. According to the noticed deviations of statistics during the project implementation, the inputs of modelling must be respectively modified to find an optimal layout of the teams forming, communication profiles, and workload distribution. It is necessary to develop an inhibitive chaos control system for mapping the areas of shortcoming forming and well-timed dynamic correction of the synergy level for introducing corrective disturbances like reasonable rework and tune-in for disposing the trajectories of shortcomings and preventing chaotic behaviour.

To analyse any process, it is necessary to have a full description of all the inputs, agents, their activities and interfaces between them during the whole designed process time as a fundamental basis. The research team has used the DSM tool for the analysis of the multi-agent systems for a long time. Fig. 7.7 presents the different DSM types. For the present study of the dynamic hierarchical teamwork system, clustering of people and teams in an organization is the most suitable type of DSM (Eppinger&Browning, 2012). Organization architecture consists of three mappings: hierarchical decomposition, work assignments and information flow. The first two are represented in the organization chart (Fig. 7.3), the third can be applied to the DSM matrix. The modelling of project teams enables us to form the most suitable meta-teams based on communication between the team's members and scheduling personal activities during the design and commissioning of a typical industrial process automation project (Browning, 2009).

The communication data are introduced to the matrix compiled by project team members (see Fig. 7.11) in a sequential order. The number of team members is practically unlimited, but the team in an average project is formed by about 30 team members. The communication and co-operation strength (synergy) presented in the matrix is characterized on three levels: low or random (0, blank), moderate (1) and strong (2). The direction of communication is very important and is readable in the matrix where priority is at the side of a bigger evaluation number. If the information flow direction is from top down, the communication is marked to a sub-diagonal part of the matrix. Above-diagonal part of the DSM matrix is filled if the information from the team member positioned below in the matrix needs to complete the task of the team member positioned above. The scope of information introduced to the matrix plays an important role in growing the synergy in teamwork.

Filling the data into the DSM input matrix forces the project team to analyse real communication needs and their frequency, providing also awareness of communication needs to the project manager and their reality. Additionally, the matrix provides an overview of the whole project and reveals possible shortcomings of critical competence and helps to discover areas uncovered in the communication pattern. At the same time, the experience and competence of the whole team is introduced to the system, giving the dimension of adaptability



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	29	30	31	32	33	
Project manager	1	1	■	2			**Owner**																													1
Technical leader	1	2	2	■	2	2																														2
Automation leader	1	3	1	2	■	2																														3
Process specialist	1	4	1	2	2	■																														4
Project manager	2	5	2	1			■	2			2	1		2	1		**Process Suppliers and Consults**																			5
Automation leader	2	6	1	2	2	2	2	■	2	2																										6
Automation Designer 1	2	7			1	1	1	2	■	2																										7
Automation Designer 2	2	8			1	1	1	2	2	■																										8
Project manager	2	9	2	1			2	1			■	2	2	1																						9
Process Designer	2	10		2	2	2		2	2		2	■	2		1																					10
Automation Designer	2	11		2	2	1		2	2		2	2	■			1																				11
Project manager	2	12	2	1			2	1			1			■	2	2																				12
Process Designer	2	13		2	2	2		2		2		1		2	■	2																				13
Automation Designer	2	14		2	2	1		2		2			1	2	2	■																				14
Project Manager	3	15	2	1	2		2	1			1			1			■	2	1			1	**Automation Supplier**													15
Lead Engineer	3	16	1	2	2	2	1	2	1	1	1	2	2	1	2	2	2	■	2	2	2	2														16
Graphics Designer	3	17		1	1	1		1	2	2		1	1		1	1	1	2	■	2	2	1														17
Configuration Engineer 1	3	18			1	1		1	2			2	2				1	2	2	■	2	2														18
Configuration Engineer 2	3	19			1	1		1		2					2	2	1	2	2	2	■	2														19
System and Hardware Engineer	3	20			1	1		2	1	1		1	2		1	2	1	2	1	1	1	■		**Commissioning Team**												20
Commissioning manager	4	21	2	2	2	2	2	1	1	1	2	1		2	1		1	1					■	2				2				1				21
Process Supplier Commissioning leader	4	22		1		1	1	2		1	1	2	1				1	2	1	1			2	■	2	2					1					22
P:S: Commissioning Engineer 1	4	23						1		1		2	2					1	2	2		1	1	2	■	2					2					23
P:S: Commissioning Engineer 2	4	24						1		1		2	2					1	2	2		1	1	2	2	■					2					24
Automation Configuration Engineer 1	4	25			1				1									1				1	2	2	2	2	■				2					25
Process Supplier Commissioning leader	4	26		1		1	1	2	1					1	2	1	1	2	1		1		2	2				■	2	2	1					26
P:S: Commissioning Engineer 1	4	27						1	1						2	2		1	2		2	1	1	1	1			2	■	2	2					27
P:S: Commissioning Engineer 2	4	28						1	1						2	2		1	2		2	1	1	1		1		2	2	■	2					28
Automation Configuration Engineer 2	4	29			1					1								1				1	2				2	2	2	2	■					29
Factory shift supervisor	4	30				1												1	1				2	2	1	1	1	2	1	1	1	■	2	2	2	30
Factory operator 1	4	31																	1					1	2	2		1				2	■	1		31
Factory operator 2	4	32																	1					1	1	1		1	1	1		2	1	■	2	32
Factory operator 3	4	33																	1					1				1	2	2		2		2	■	33
			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	29	30	31	32	33	

Figure 7.11. Communication matrix data after DSM clustering (Källo, 2016)

to it. The DSM technology enables us to visualize the communication map and use further DSM mathematical treatment to optimize the composition of the working groups and cluster most capable meta-teams where the communication is more vigorous. The coloured rectangles represent a new meta-teams suggested by the DSM tools.

The mathematical processing of the DSM matrix indicates that it is unreasonable to handle consulting and process design teams separately; instead, it is useful to integrate them into one meta-team where the communication is smoother and direct, not considering the contractual boundaries of different companies involved. Similar behaviour is expected for commissioning engineers and factory employees. They need to be treated as group members apart from organizational and financial aspects. In addition to meta-team's internal communication, there is a certain amount of external communication with other teams presented. Communication between meta-teams can be handled by appointing appropriate liaisons with suitable skills and expertise to organize information exchange between the meta-teams. As a result, the chaotic behaviour of the hierarchical teamwork system can be substantially reduced using the DSM technology. Mathematical tools reveal the problems in the communication structure and decompose working groups into cross-functional teams. The information transfer is a basis for planning the application of integrative mechanisms in the project, including communication planning, regular meeting scheduling, planning workplaces and co-locating meta-teams, compiling e-mail distribution lists, appointing liaisons, etc. Manipulation of DSM communication patterns enables us to create alternative layouts of organizational structure and to find an optimal one for project success. However, the DSM is static and does not consider the time factor. The time can be introduced to the analysis by using soft computing tools and discrete event modelling.

Adopting the results of DSM matrix tools to the organizational structure gives better results in the project outcome due to organized and deliberated communication patterns. As a direct outcome from the following recommendations of the matrix readout, faults F can be mitigated by setting the cooperation and communication procedures by the determination of the responsibilities. The strategic miscalculations S can also be minimized, but only at the beginning of the project, during business negotiations. Financial and technical tasks and rules must be always very clearly defined. The scheduling and sequencing of the activities is very important, as the next group can start their work after the previous has finished a certain part of their task. It is clear that scheduling does not exclude later clarification of the task or rework caused by new knowledge obtained during the project. The liaison activity between the groups also needs to be scheduled and organized to ensure a smooth information transfer (Källo et al., 2015).

Communication in the project hierarchical teamwork system is usually organized according to the work assignments and decisions to be made inside the project. The scheduling of teamwork is supervised by the project manager and team leaders. However, substantial direct communication between the team members is also occurring, but the schedule is somewhat random and uncontrolled. The initiator of information exchange is usually the team member who needs certain input to perform a specific task. These task performing schedules are normally managed by project leaders but the final communication pattern is dependent on the team member's qualification, personalities, historical and cultural profiles, geographical locations, working habits, motivation, etc.

The scheme in Fig. 7.12 shows a traditional hierarchical reality structure of the project teams created on the basis of involved companies and concluded contracts (on the basis of Fig. 7.3). Small teams are supervised through the project by an owner's team. Communication between the team members is represented by arrows of two colours, where violet marks moderate interaction and red accordingly strong communication and cooperation. The direction of the arrow represents the initiator of communication, i.e., one person passing over the information to another or requesting an explanation. Communication can be also bidirectional in mutual discussions and meetings.

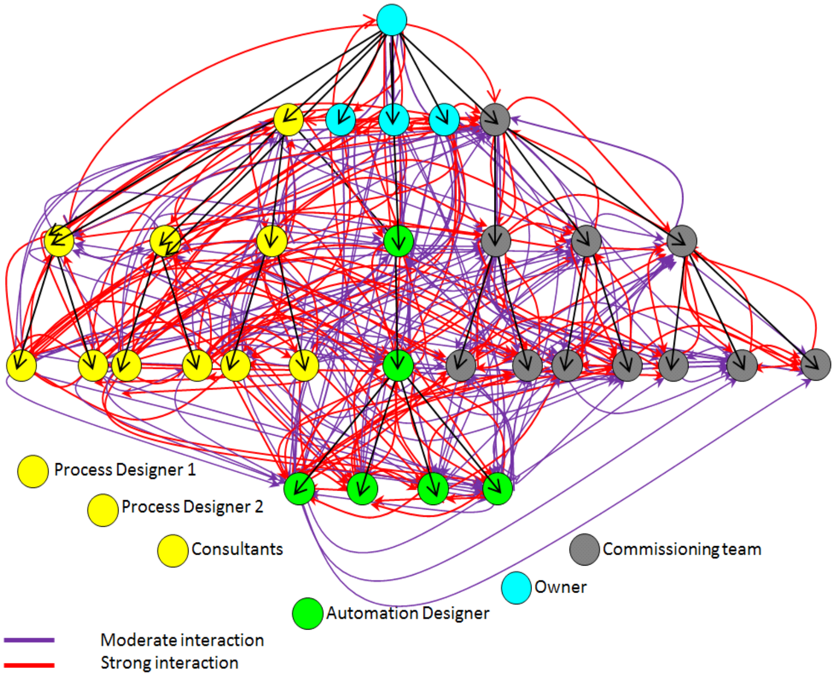


Figure 7.12. Graphical representation of hierarchy and communication in the process automation project (Källo, 2016)

Now one can imagine how sensitive this multi-agent hierarchical teamwork system is to tainted and imperfect information transfer. An agent's decisions or actions are dependent on the decisions made by other agents with an upper position in the information flow. Consequently, transfer of imperfect information leads to poor decisions and exponential increase of chaotic behaviour, downgrading the performance of the whole teamwork system. Such a "butterfly effect" where small reasons can have large effects may result in a real chaos in the industrial process automation project. In the case of poor decisions, the trajectory of an actual process shows a difference as compared to that predicted and the amount of shortcomings in a particular subsystem is increasing, pushing the process trajectory towards catastrophe (see Fig. 7.13).

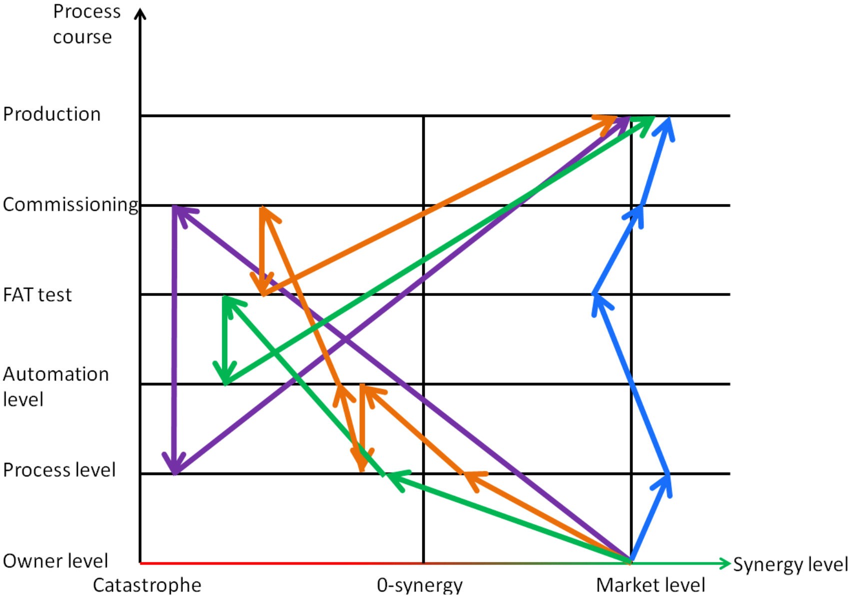


Figure 7.13. Example trajectories of shortcomings (Källo, 2016)

As an example of growing chaotic behaviour in the teamwork system, a violet arrow indicates a wrong decision made in the process level, caused by insufficient information from the owner level. The problem escalates in the automation level, is passing the FAT test and is discovered only during commissioning. To fix the situation, a certain amount of rework is required; starting from the process level where the reason for a shortcoming is fixed and new information is forwarded to the next levels. In the automation level, some redesign is needed, which requires new testing procedures to be carried out before entering the commissioning stage with that particular issue. After successful test and commissioning, the issue is ready for the production state. Nearly ideal situation with communication and information exchange is presented with a blue line where all the decisions and actions are based on mainly correct and comprehensive information and the line describing work amount is considerably shorter, meaning that the result is achieved with minimum contribution to the working hours and the result is somewhat better than expected. Orange line represents the situation where a single problem requires rework in more than one occasions before the solution is acceptable. However, necessary rework is relatively small in both occasions, descending only by one level. The green path is visualizing a problem similar to that of the violet line where the rework is considerably smaller, as the problem is discovered during the FAT and reworked in the automation level without moving deeper into the structure.

To prevent the growth of chaos, it is necessary to create an effective system of tracking and hindering a variety of human shortcomings spreading in the dynamical hierarchical teamwork system. The formation and spreading of shortcomings is a fully accidental process; accordingly, all the decisions and actions in the system can turn somehow chaotic. However, the chaotic behaviour in the hierarchical teamwork during the project implementation never ends with a catastrophe where all the project-related activities stop for technical or teamwork reasons. All the impacts of the shortcomings are normally removed during commissioning and the production is launched, but with a delay.

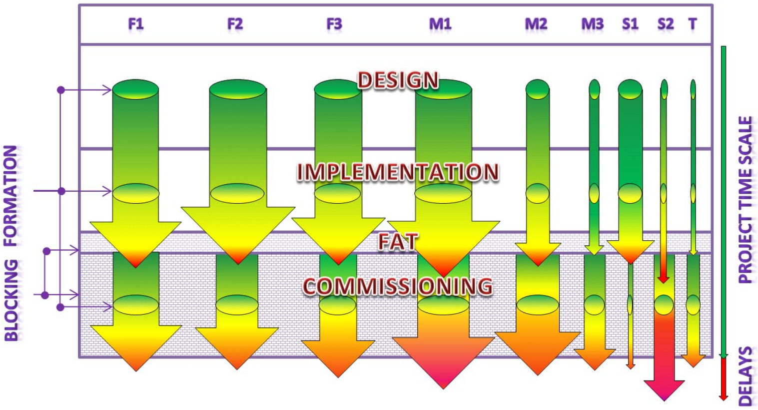


Figure 7.14. Impact of shortcomings on the whole project time (Källo, 2016)

Figure 7.14 shows the spreading of quantified shortcomings in the time scale of project implementation. The duration of the sample project is considered to be one year. The formation zones of shortcomings are shown as integrated, considering the fact that origination of the human fault or mistake may happen at any moment on the time-scale. FAT and commissioning are shown here as blocking zones of shortcomings where the deviations are discovered. Horizontal dimensions of the arrows represent the statistical share of the shortcomings. The length of the arrow of shortcomings presents the real working hours spent on the correction of the impact of a specific shortcoming calculated from an average project and based on the real shortcomings database. The overrun of the longer arrows on the time-scale shows the delay of the project start-up in the sample project. In real life, the delay is conditional, as it depends on the availability of human resources with necessary competence that can be concentrated at the elimination.

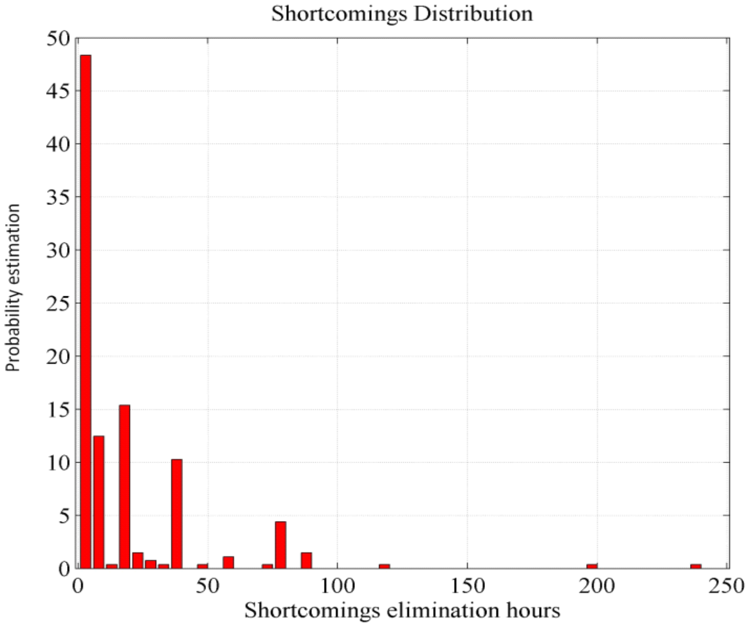


Figure 7.15. Probabilistic prediction of the time for removal of the consequences of shortcomings (Källo, 2016)

From the results of the analysis of the shortcomings database, an anticipated probabilistic prediction of the time needed to eliminate the shortcomings was found during the design and commissioning of the process automation systems (see Fig. 7.15). The vertical axis shows the percentage of probability of elimination of the consequences of shortcomings, when the rework of a certain amount of hours is required (horizontal axis). From the shortcomings distribution graph, it is obvious that the probability of small problems is considerably higher than the time-consuming ones. However, the impact of small problems cannot be underestimated, as even simple mistakes can start the receding of the process trajectory from an ideal one and be a source of chaos growth in the system.

Today the shortcomings are mainly revealed in two blocking zones of the project (see Fig. 7.14) where, as a rule, communication procedures are overlooked. To react to problems more efficiently, it is essential to create a dynamic tracking system on the basis of statistical evaluation of human shortcomings that helps to discover the growth of chaotic behaviour, with the focus on the critical areas in the communication pattern. The critical areas of communication, where the probability of the formation of shortcomings is highest, can be identified by applying the shortcomings data from the empirical database to the team structure matrix. Additional smaller blocking zones need to be created for the prompt reaction to the appearance of shortcomings. Further discrete event modelling brings the time factor into the analysis process, allowing finding the best communication matrix and an optimal team structure to minimize the time for rework and iterations during project implementation.

7.5. Reducing project duration by empowering synergy in teamwork

Whatever project and forecast of time, it is necessary for the owners and management to start time planning from the very beginning of the project up to its realization. For factory process automation or renovation, realization means attaining the production in full. It is a complicated task because modified or new or corrected necessary information is supplied occasionally during project implementation, causing iterations and rework.

In principle, there are two ways of planning the project duration – a deterministic and a probabilistic approach. Earned value management (EVM) methodology is one of the most straightforward and common deterministic methodologies for project monitoring (Vanhoucke&Vanhoucke, 2015; Spiropoulos, 2015). It is common knowledge that in reality the project implementation is always late. On the basis of previous experience, it is reasonable to add about 5% to the estimated time. At first glance, it may seem to be small influence but if you add here the production not acquired, it is a loss in some or in tens of millions.

Probabilistic approach has a larger degree of variations and the result includes distributions and confidence intervals around the estimated date. Due to the complexity of the present task and the fact that deterministic methods cannot handle the dynamical structure of the teamwork in the conditions of accidental human shortcomings, the only way is prognosis of project duration by probabilistic modelling using soft computing tools.

Development of the proposed probabilistic methodology for project duration prognosis can be divided into two stages. First, an average probabilistic duration of the project using traditional project planning methods by addition of the statistics of human shortcomings is computed. The second stage is to suppress the impact of chaotic behaviour of the teamwork caused by human shortcomings. It should be done by empowering synergy in the teamwork with appropriate handling the discovered shortcoming trajectories to reduce the project duration previously predicted.

A suitable modelling technique for the system performance evaluation seems to be computing the duration using parallel discrete event simulation (Pritsker&O'Reilly, 1999; Zeigler et al., 2000, Cho, 2001). In this model, the events trigger the transitions and time progresses in discrete steps between the events. Parallel simulation enables more than one component to be active at the same time and send the outputs to other components. The Latin Hypercube Sampling method is more suitable for the expected durations, including possible iterations in the system (Cho&Eppinger, 2001). An event is defined here as a cooperation or communication activity. The model initializes the variables, adjusts the durations of the tasks and generates the sequential iteration rework, using a probabilistic rule and computing probability distributions for the expected durations. The expected duration of an agent's time allocation is based on the probabilistic experience-based prediction. However, there is some spare time reserved for handling the shortcomings. The model takes into account the working hours available for rework probability, learning curve, and team composition.

The project duration computation model using the tools of DSM and Latin Hypercube Sampling is presented in Fig. 7.16. The inputs for the system performance evaluation model are as follows:

- List of agents participating in the project;
- Communication pattern of teamwork;
- Working time estimate for every agent based on the tasks with rework risk tolerance and learning curve.

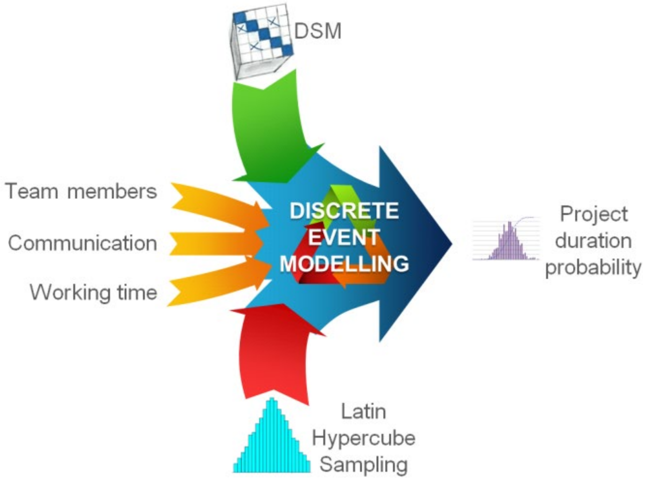


Figure 7.16. Modelling of probable duration of a project (Källo, 2016)

First, the project duration is calculated using traditional approach to the industrial process automation system design and commissioning where the teams are based on companies and contracts and communication is scheduled considering an optimistic scenario of fully successful co-operation. The tasks are planned as sequential and parallel, provided that the team below in the matrix (Fig. 7.11) starts the work after the information package from the team above is handed over. For testing the proposed methodology, the average project duration was used for discrete event modelling, based on the experience generalized from the shortcomings database. Total working hours for this example project were calculated to be 12,000 h (100%) and the duration of the project was considered to be one year. To present results more clearly, the duration was transferred to % scale.

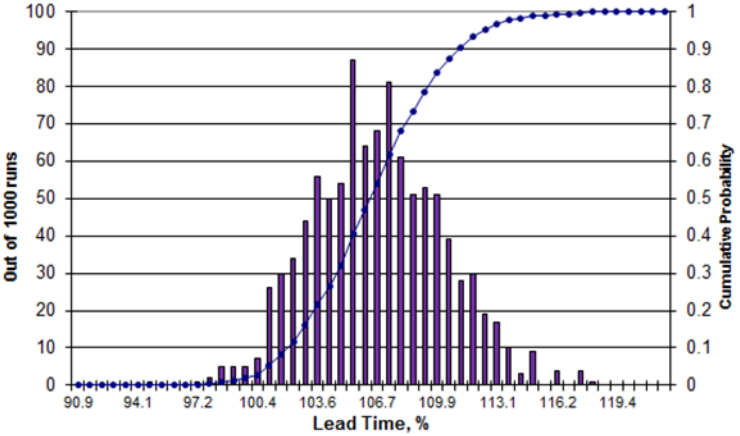


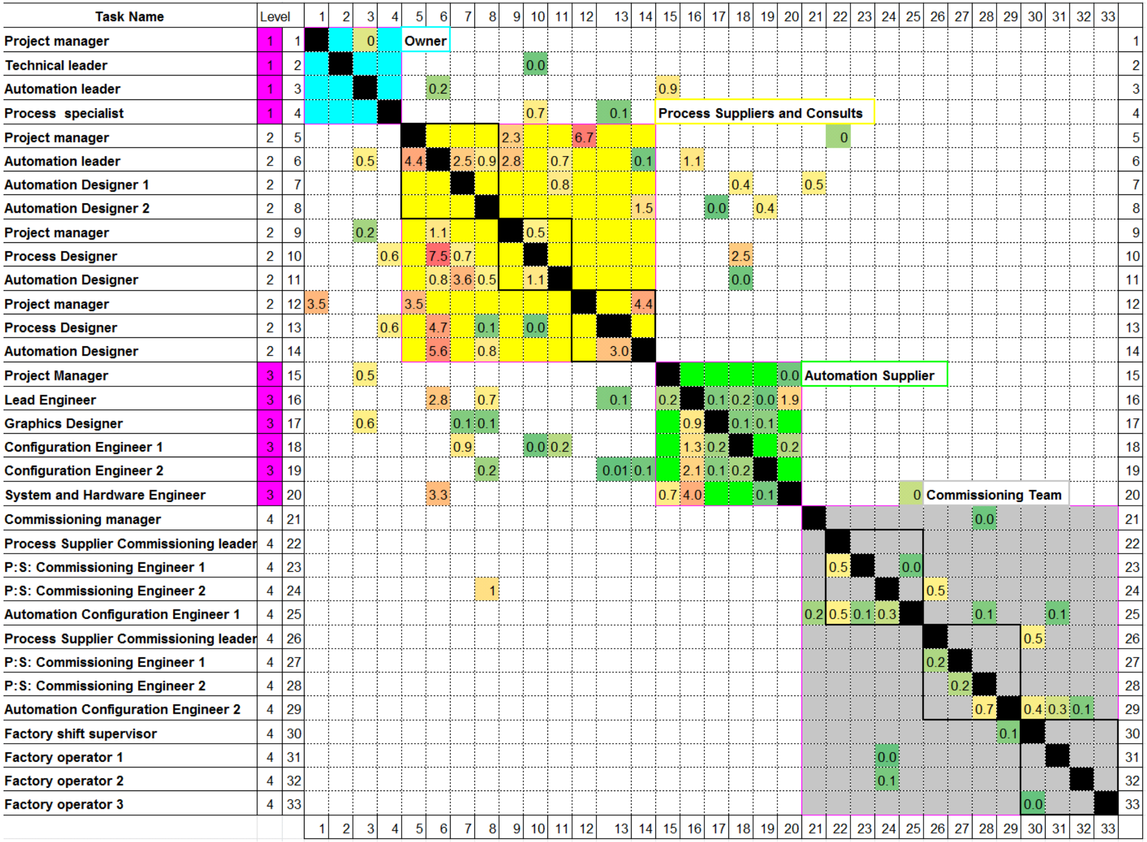
Figure 7.17. Possible duration of the project as a discrete event modelling result (Källo, 2016)

The output of discrete event modelling is the chart of sampling results enhanced with the cumulative probability see curve (Fig. 7.17) where the probable project duration can be seen. The nominal duration of 100% is expected to be by the conditional schedule, overlooking human shortcomings and their chaotic dissemination. However, taking into account the human shortcomings data (see section 7.3), the real duration of the project schedule is exceeded by 6.5% with a cumulative probability of 0.5. As Fig. 7.17 shows, there is a very slight possibility to finish the project in schedule if the corrective actions for tracking and hindering the shortcomings are not implemented and communication schedule not considered and updated. The value of the proposed methodology is in the addition of the real dispersion area to the traditional project implementation time, caused by inevitable human shortcomings and estimated on the basis of their statistics.

From this basis, it is appropriate to start development of a new approach targeted to reducing the project duration. Project communication schedules and procedures need continuous upgrading to empower synergy and find possible ways to shorten the project duration by possible fast elimination of the influence of human shortcomings. The fundamental basis for the development of this upgraded approach for communication schedules is a modified picture of all agents, tasks, inputs, activities, and interfaces between them, using the DSM technology. To point out the critical areas for origination of shortcomings, it is necessary to map the starting points of chaotic behaviour dissemination by evaluating the weight of the fault or mistake and its dissemination area (Källo et al., 2016).

Further analysis of the human shortcomings database considering origination of the problems in the communication network and the time needed to eliminate them in the shortcoming blocking zones is visualized in Fig. 7.18. From the database, the impact of the shortcomings on the rework hours was transformed into a percentage scale and the efforts needed to finalize the project were introduced to the clustered matrix form. The per cent- weight of the shortcomings was marked to the cell where the communication problem arose.

The analysis shows that a majority of the problems fall to the area of clustered meta-teams (blue, yellow, green and grey areas), indicating a need for reforming to reduce the communication insufficiency. Most common company-based team structure is shown with black bordered rectangles. The idea of dynamical temporary meta-teams is based on the author's professional experience (Källo, 2016). According to this experience, the communication quality inside new teams is increased, allowing also reduction of the amount of arrival of the human shortcomings. Meta-teams involving persons from different companies relieve the communication boundaries and bureaucracy, enabling smooth co-operation (Källo et al., 2012). It is obvious that the communication pattern in the areas marked red, orange or yellow has not been satisfactory and requires improvement.



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	29	30	31	32	33	
Project manager	1	1	■		0		Owner																													1
Technical leader	1	2		■								0.0																								2
Automation leader	1	3			■			0.2									0.9																			3
Process specialist	1	4				■						0.7			0.1		Process Suppliers and Consults																			4
Project manager	2	5					■				2.3			6.7										0												5
Automation leader	2	6			0.5		4.4	■	2.5	0.9	2.8		0.7			0.1		1.1																		6
Automation Designer 1	2	7							■				0.8							0.4			0.5													7
Automation Designer 2	2	8								■						1.5			0.0		0.4															8
Project manager	2	9			0.2			1.1			■	0.5																								9
Process Designer	2	10				0.6		7.5	0.7			■								2.5																10
Automation Designer	2	11						0.8	3.6	0.5		1.1	■							0.0																11
Project manager	2	12	3.5				3.5							■		4.4																				12
Process Designer	2	13				0.6		4.7		0.1		0.0			■																					13
Automation Designer	2	14						5.6		0.8					3.0	■																				14
Project Manager	3	15			0.5												■					0.0	Automation Supplier													15
Lead Engineer	3	16						2.8		0.7					0.1		0.2	■	0.1	0.2	0.0	1.9														16
Graphics Designer	3	17			0.6				0.1	0.1								0.9	■	0.1	0.1															17
Configuration Engineer 1	3	18							0.9			0.0	0.2					1.3	0.2	■		0.2														18
Configuration Engineer 2	3	19								0.2					0.01	0.1		2.1	0.1	0.2	■															19
System and Hardware Engineer	3	20						3.3									0.7	4.0			0.1	■					0	Commissioning Team								20
Commissioning manager	4	21																					■							0.0						21
Process Supplier Commissioning leader	4	22																						■												22
P:S: Commissioning Engineer 1	4	23																						0.5	■		0.0									23
P:S: Commissioning Engineer 2	4	24								1																■		0.5								24
Automation Configuration Engineer 1	4	25																					0.2	0.5	0.1	0.3	■			0.1			0.1			25
Process Supplier Commissioning leader	4	26																										■				0.5				26
P:S: Commissioning Engineer 1	4	27																										0.2	■							27
P:S: Commissioning Engineer 2	4	28																											0.2	■						28
Automation Configuration Engineer 2	4	29																												0.7	■	0.4	0.3	0.1		29
Factory shift supervisor	4	30																													0.1	■				30
Factory operator 1	4	31																								0.0							■			31
Factory operator 2	4	32																								0.1								■		32
Factory operator 3	4	33																														0.0			■	33
			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	29	30	31	32	33	

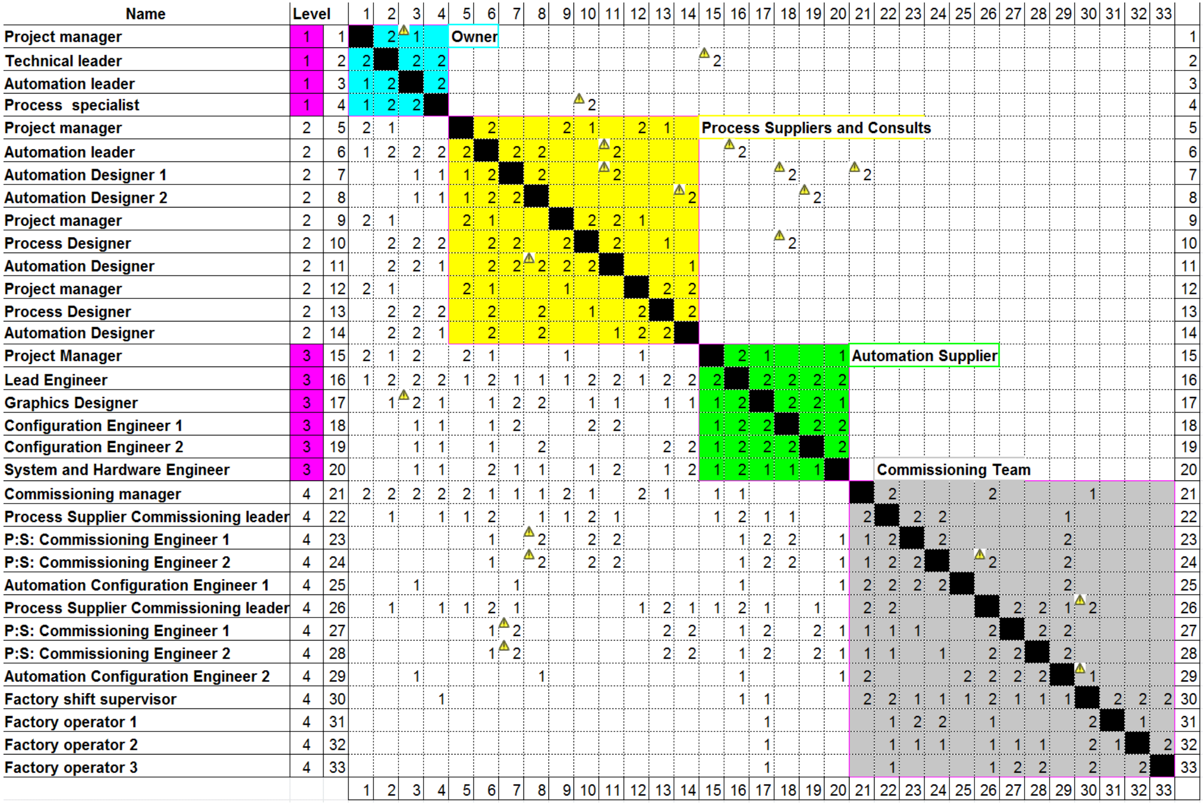
Figure 7.18. Mapping of shortcomings in the DSM matrix (Källo, 2016)

The upgraded communication map (see Fig. 7.18) is compiled in a 3-level scale, where 0 (blank) represents random non-planned communication, 1 stands for moderate, and 2 for strong scheduled face-to-face communication and tight cooperation in daily work. Some of the sources of chaotic shortcomings cannot be considered on the scheduled communication map, so the matrix needs continuous upgrading by adding and modifying the communication rules. At scheduling a new communication map for meta-teams, the problematic areas in the matrix need to be improved by mapping additional communication points into the patterns or increasing the strength of existing ones (see Fig. 7.19, marked with⚠). Also, if no communication problems have occurred in a specific area, it might be reasonable to lower the communication level. However, changes in the cooperation profile need to be handled case-by-case without changing the existing successful communication network.

The critical percentage where the communication matrix needs improvement was set at 0.3% of total time needed for rework. The values below 0.3% were considered as casual problems that need no regulation. As some of the new communication schedule marks are located outside the meta-teams blocks, it is reasonable to schedule communication between the meta-teams by appointing liaisons for certain subjects communicated. To evaluate the impact of the enhanced communication pattern based on empirical studies, it is necessary to use tools of discrete event modelling to predict project duration with renewed initial data.

The proposed methodology of meta-team forming is inevitable to support the optimization regarding the reduction of the project implementation time. Traditionally, similar solutions are made on the basis of intuition, but human brain is able to work out only simple solutions. In more complicated situations, it is possible to optimize reactions on growing chaos only through multiple meta-teams formation and to verify their optimality by discrete event modelling.

To reduce the influence of human shortcomings and faulty communication on the teamwork system, it is necessary to introduce the synergy-based activities to raise the quality of teamwork. DSM-based mapping of the communication structure increases the comprehension of interactions so that right information can be made available at the right place and at the right time (Browning, 1999). Additionally, the impact of delays in information transfer can be identified by tracking the information flows. Such improvement efforts as changing the communication pattern, allocating additional resources, overlapping the tasks introduced to the model are reducing the risk of delays in the teamwork system (Cho, 2001).



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	29	30	31	32	33	
Project manager	1	1	■	2	⚠1		Owner																													1
Technical leader	1	2	2	■	2	2											⚠2																			2
Automation leader	1	3	1	2	■	2																														3
Process specialist	1	4	1	2	2	■						⚠2																								4
Project manager	2	5	2	1			■	2			2	1		2	1		Process Suppliers and Consults																			5
Automation leader	2	6	1	2	2	2	2	■	2	2			⚠2					⚠2																		6
Automation Designer 1	2	7			1	1	1	2	■	2			⚠2							⚠2			⚠2													7
Automation Designer 2	2	8			1	1	1	2	2	■						⚠2					⚠2															8
Project manager	2	9	2	1			2	1			■	2	2	1																						9
Process Designer	2	10		2	2	2		2	2		2	■	2		1					⚠2																10
Automation Designer	2	11		2	2	1		2	2	⚠2	2	2	■			1																				11
Project manager	2	12	2	1			2	1			1			■	2	2																				12
Process Designer	2	13		2	2	2		2		2		1		2	■	2																				13
Automation Designer	2	14		2	2	1		2		2			1	2	2	■																				14
Project Manager	3	15	2	1	2		2	1			1			1			■	2	1			1	Automation Supplier													15
Lead Engineer	3	16	1	2	2	2	1	2	1	1	1	2	2	1	2	2	2	■	2	2	2	2														16
Graphics Designer	3	17		1	⚠2	1		1	2	2		1	1		1	1	1	2	■	2	2	1														17
Configuration Engineer 1	3	18			1	1		1	2			2	2				1	2	2	■	2	2														18
Configuration Engineer 2	3	19			1	1		1		2					2	2	1	2	2	2	■	2														19
System and Hardware Engineer	3	20			1	1		2	1	1		1	2		1	2	1	2	1	1	1	■		Commissioning Team												20
Commissioning manager	4	21	2	2	2	2	2	1	1	1	2	1		2	1		1	1					■	2				2				1				21
Process Supplier Commissioning leader	4	22		1		1	1	2		1	1	2	1				1	2	1	1			2	■	2	2					1					22
P:S: Commissioning Engineer 1	4	23						1		⚠2		2	2					1	2	2		1	1	2	■	2					2					23
P:S: Commissioning Engineer 2	4	24						1		⚠2		2	2					1	2	2		1	1	2	2	■		⚠2			2					24
Automation Configuration Engineer 1	4	25			1				1									1				1	2	2	2	2	■				2					25
Process Supplier Commissioning leader	4	26		1		1	1	2	1					1	2	1	1	2	1		1		2	2				■	2	2	1	⚠2				26
P:S: Commissioning Engineer 1	4	27						1	⚠2						2	2		1	2		2	1	1	1	1			2	■	2	2					27
P:S: Commissioning Engineer 2	4	28						1	⚠2						2	2		1	2		2	1	1	1		1		2	2	■	2					28
Automation Configuration Engineer 2	4	29			1					1								1				1	2				2	2	2	2	■	⚠1				29
Factory shift supervisor	4	30				1												1	1				2	2	1	1	1	2	1	1	1	■	2	2	2	30
Factory operator 1	4	31																	1					1	2	2		1				2	■	1		31
Factory operator 2	4	32																	1					1	1	1		1	1	1		2	1	■	2	32
Factory operator 3	4	33																	1					1				1	2	2		2		2	■	33
			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	29	30	31	32	33	

Fig. 7.19. Upgraded communication matrix (Källo, 2016)

A meta-team's structure makes its own corrections in the classical project management activities. Inside meta-teams, it is necessary to form a dynamical self-organizing task-oriented structure according to agile project management philosophy. Flat organization structure enables seamless communication and cooperation and allows saving the project from unnecessary activities of bureaucracy of management. In case of geographical distance between the team members, the need for coordination is higher and the communication structure is more scheduled instead of proximate face-to-face discourse. With agile project coordination principles, the rework caused by human shortcomings can be made in parallel instead of conventional serial work, as inside the meta-teams, each agent can start their operations based on the first hand communication instead of waiting for an information package to be handed over.

Table 7.1. Data setups for additional time allocation (Källo, 2016)

	Additional time, %	Time saved, %	Average duration, %
Set 1	**20**	**40**	**85.4**
Set 2	**40**	**55**	**86.2**
Set 3	**60**	**70**	**86.9**

In the present case, experience-based data are introduced to the dynamical model to find out an optimal additional time distribution based on data about shortcomings and their causal analysis. There may be different experience-based setups of data for modelling used at allocating additional time of team members based on the empirical data of human shortcomings and their removal time (see Table 7.1). The critical problem for every project leader is how to divide the rework time for necessary iterations in the project work. According to the assumption based on long-term experience (Källo. 2016) in the realization of process automation projects, the probability of wrong decisions is decreasing about 40% when the possible source of shortcomings has 20% more time for completing the task. In the same way, it is possible to state that 40% of additional time lowers the probability of poor decisions by 55% and 60% of time contribution leads to reduction of shortcomings probability by 70%. The percentage of additional time is calculated from the time spent for rework to eliminate the impacts of human shortcomings. But these assumptions must be approved by modelling.

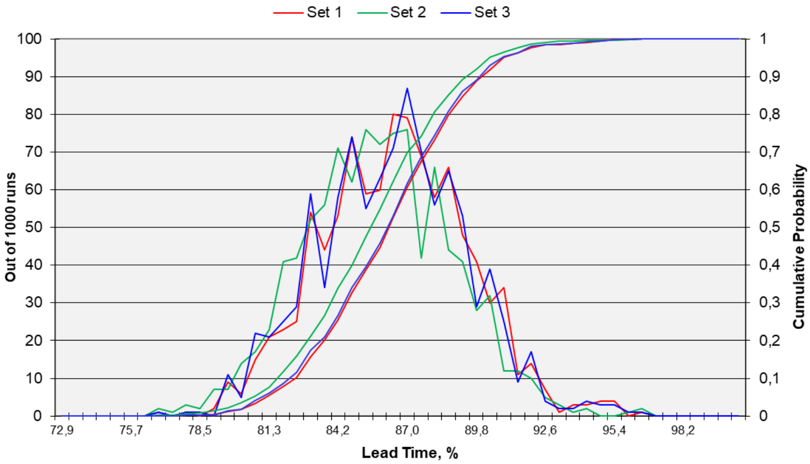


Figure 7.20. Modelling results with different time distributions (Källo, 2016)

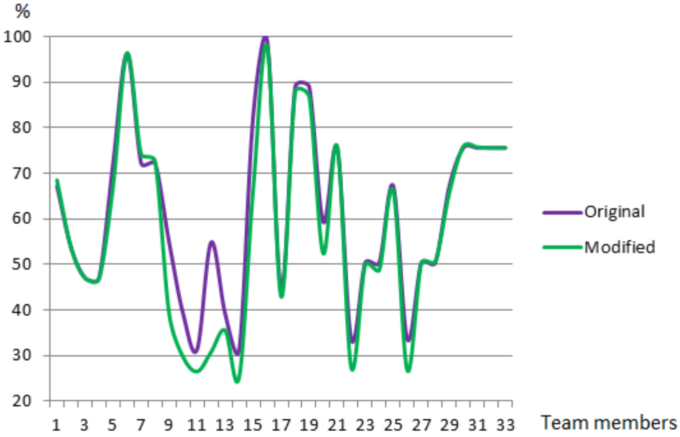


Figure 7.21. Modifications in the time distribution between the team members (Källo, 2016)

Discrete event modelling of probabilistic duration of the project shows (see Fig. 7.20) that the use of data set 1 is an optimal solution, where 20% of time spent for rework is distributed between the team members that were responsible for making wrong decisions that started the chaotic behaviour in teamwork. Figure 7.21 shows the time distribution graph where the original values stand for the allocated working time from a traditional project schedule and the modified graph represents the time distribution after modifying time allocation based on the empirical research of human shortcomings. The changes in the time allocation are relatively small, but are giving significant results on shortening the project duration due to the so-called ”butterfly effect“.

For final modelling, all the proposed assumptions were applied: enhanced meta-team’s structure with agile project handling methods allowing more parallel operations instead of sequential, improved communication pattern considering empirical results of the shortcomings database, and continuous tracking of occurrence of shortcomings to minimize the chaos dissemination. The automation system often becomes the critical part of production start-up as it is the final element to be implemented. Process equipment as a whole needs to be installed and working before the control system can be finally commissioned and tuned. Thus, the parallel activities for rework become extremely important to minimize the delays causing problems with the realization of revenues of an industrial plant due to late start-up. In summary, the presented methodology of discrete event modelling enables computing probability distribution of task implementation time in the project matrix where iterations and rework take place in sequential and parallel tasks.

Now it is appropriate to evaluate the impact of the proposed synergy-based modified methodology for the realization of a real industrial automation project. The discrete event modelling results in reveal significant shortening of project realization time - from 106.5% in Fig. 7.17 to 85.4% in Fig. 7.22 with the cumulative probability of 0.5. This assures that the planned production start-up date will not be exceeded and refers to significant savings on the labour cost. It is necessary to underline here that these are theoretical limits for capable competent teams. Inexperienced teams under incompetent management of the project may cause a relevant increase of time losses prognosis.

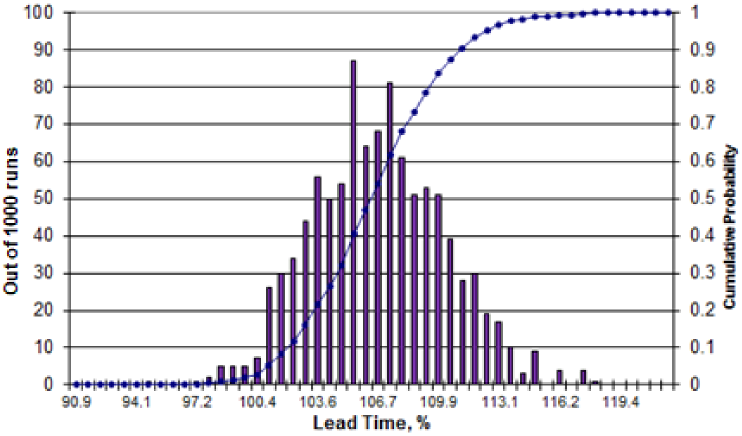


Figure 7.22. Possible duration of the project after using proposed methodology (Källo, 2016)

Table 7.2. Labour costs during project implementation (Källo, 2016)

	Position	Hourly rate €	Conventional method, €	Synergy-based approach, €	Savings €
	Project managers	160	318 500	261 300	57 200
	Lead engineers	130	342 450	331 500	10 950
	Engineers	100	615 700	593 000	22 700
	Operators	70	95 250	95 300	-50
	TOTAL		**1 371 900**	**1 284 100**	**87 800**

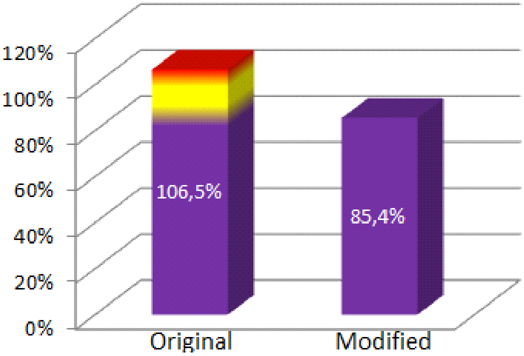


Figure 7.23. Comparison of average project duration prognoses (Källo, 2016)

Figure 7.23 compares the modelling results of the project implementation duration at the original conventional approach to project management with the proposed modified approach striving for better synergy in project teamwork. In the first case, the prognoses duration is 106.5% from which 6.5% is caused by human shortcomings (marked red). At the modified approach, the duration prognosis is 85.4% where reduction due to the synergetic approach to teamwork system dynamics is 14.6% (marked yellow). On the other hand, at the overall shortening of the prognosis of project duration of about 21%, the savings in the project implementation at direct labour costs of 6.7% are impressive (see Table 7.2). Thus, the proposed modified methodology for growing the synergy level in the hierarchical teamwork system by handling human shortcomings and besieging their chaotic dissemination is successfully verified and proved to be beneficial.

CONCLUDING REMARKS

V. Reedik

Reflecting on the studies of synergy-based thinking deployment described in the present book, two periods can be distinguished depending on the situation in the field of computer technology. During the first 20 years, we had some computer support for modelling of aerodynamic processes. But after a five-year higher education rearrangement pause, we were provided an opportunity to enjoy the advantages of soft computing and discrete event modelling support. Therefore, we can distinguish two research periods: one of experimental and the other of empirical synergy studies.

In the first period, the high accuracy aerodynamic relay effect at penetrating inclined scale into laminar jet was discovered, which allowed the development of the positioning sensors with repeatability of switching ±0.6 μm. On basis of these sensing elements, a relay pneumo-hydraulic servo drive was built, where the control signal spreads close to the sound speed and allows positioning at the accuracy of ± 0.01 mm. During the second half of this experimental period, different types of backpressure sensors were studied to use qualitative synergy effects for the increase in their accuracy. Then, to attain synergy of pressure and cooling in pneumatic massage devices, the fluid dynamics finite volume computational modelling was used.

At the turn of the century, main attention was shifted to flexible methodologies for interdisciplinary systems design. Our research group focused on the empirical studies of the reasons of "bad engineering" or negative synergy in teamwork. Therefore, the second period of research was fully devoted to the development of the philosophy of synergy-based design to integrate the different technologies, market conditions, reliability and quality problems and human factors in multi-agent teamwork into the powerful concept of synergy-based product development. On this journey, we started with the study of mechatronic office machines, expanding further in the direction of systems engineering, modularization, production system automation and multi-agent teamwork optimization, grasping all it into the total quality assurance environment.

What are the findings met on this complicated and winding research track?

First, in the world of different product and system development, synergistic thinking proved to be an excellent binder and consolidating phenomenon for technologies integration. Without doubt, synergy has been really a nameless motivator on the long way of technology development during the traceable period of human existence.

Secondly, it is expedient to distinguish the terms positive and negative synergy. Positive synergy appears as the result of compensation of mutual deficiencies and boosting the useful effects between the allied technologies. Negative synergy between the technologies was proved experimentally and in human relations empirically. To evaluate the latter, representative and trusted databases were completed. The effects of negative synergy must be pressed down during the whole system development process and the first steps of the product on the market. Fighting for positive and against negative synergy does not happen automatically; rather it needs strenuous and competitive effort of every team member.

Thirdly, it is obvious that the time of prescriptive and descriptive engineering system design methodologies is over and it is reasonable to give way to methodologies adaptive to team member's competence. It means that every design team will compose its own roadmap of activities, leading to the purpose at the shortest possible time. A good chance to do so is to combine Design Structure Matrixes technology and Theory of Design Domains, which allows compiling the matrix introducing personal competence by writing into the matrix all weighted interactions between the acting agents. The further planning of activities is realized by the mathematical treatment of matrixes.

Fourth, for an planner of every project, it is very important to know the time needed for the team to reach to the end goal – to the launch the production of a designed object. Here it is necessary to take into account iterations and reworks with learning curves based on empirical data from similar projects. This is possible by probabilistic prognosis of project time using the discrete event modelling technology.

Fifth, this book is based on the experience of the non-safety critical product and system development. But if you remove the marketing barriers on the positive synergy axis and change them to the specific barriers of those of safety-critical world using corresponding databases, the principles described above are applicable too.

Sixth, deep constraints between synergistic development of nature and influence of jungle law on human society development were observed. More details will be shared at the end of present conclusions.

What is the useful knowledge and experience an attentive reader may draw from this book?

We assume that the main value of the book is in the real case studies. However, the chapter of experimental synergetics carries a conclusive style and for practical help, it is necessary to turn to original sources in references. But the following seven case studies have been compiled in the present century and are detailed enough for their direct use.

Chapter 3 is devoted to the development of a synergy-based design philosophy for interdisciplinary products and systems integration. At the beginning of the research, the focus was on of the concepts of negative and positive synergy. For the study of negative synergy, the reliability of behavior between the mechanical, electronic and software components of new mechatronic office machines during the infant mortality period was established. This research was based on a capacious database containing more than 3000 service actions. In a separate study, negative synergy in teamwork was analyzed using the industrial database of light fittings design and production. It is obvious that the results of the above studies of negative synergy are empirical, having probabilistic character. Therefore, they can be valuable information for prognoses. As a case study, the prognosis of the competitive dependability/price ratio of a newly developed copying machine is presented. As a result, a synergistic look at the interdisciplinary systems design is addressed, which is based on pressing down mutual weaknesses or negative synergy and the amplification of useful effects or positive synergy between the allied technologies.

In Chapter 4, a novel adaptive synergy-based methodology for engineering design of interdisciplinary systems is presented. It is shown that for technologies integration it is appropriate to use the combination of the Theory of Design Domains and the Design Structure Matrixes technology. To get involved in real engineering experience to the design, a unique database of human and technical shortcomings was compiled, comprising the design and launch information of more than 13,000 equipment control systems in Northern countries. The practical realization of the proposed methodology is demonstrated on the basis of a case study, which was initiated to raise the accuracy of the existing but failed pneumatic positioning system. In this case study, by help of the synergistic approach, a correction mechanism with a cheaper shortest roller slide and friction-free elastic pneumatic drive, which is controlled by the pressure proportional to the positioning error, was developed. The validity of the proposed approach has been proved experimentally and the modernized positioning system has demonstrated its increased accuracy at a competitive market price. As a result, a family of adaptive design tools was developed, based on the level of competence and expert knowledge of the design team.

The relations between synergy and quality are in the spotlight of Chapter 5. The research was focused on integrating the synergy-based engineering design methodology and quality management into one effective quality assurance framework. To clear up the synergy and quality relations, the quality-synergy relations matrix in the context of the interdisciplinary systems design was compiled. As a result, the quality and synergy correlation is quite impressive - on the medium level 67% and 10% on the strong level. This was an encouraging basis for the further use of synergy-based thinking as a meta-tool for integration of the product development and quality assurance system. Further, the matrixes of Total Quality Management were integrated with a synergy-based design matrixes system. To involve the real-life experience, a 10-year database of human shortcomings was compiled where the results of the quality management certification processes of more than 200 production companies were analysed. It was proved that the integrated model of system design and quality management is an effective novel tool that enables building in the quality into the product from the first steps of its development with the help of an empowered quality certification process.

In Chapter 6, the synergy-based approach was extended to the design of complex modular products and multi-agent production systems. To explore the problems of modularization, a real case study of developing a modular product - a test adapter for functional and electrical testing of mobile phones - is analysed. It is shown that the use of Design Structure Matrix technology is a powerful tool for clustering product architecture and giving a good change to combine it with design activities of modular systems. To attain better synergy in the development process, the principle of expedient modularization was developed, which allows modularization from the very beginning of product development.

In the ever growing progress of product and process development, medium and small enterprises happen to be caught into a trap. On the one hand, it is necessary to increase production efficiency, flexibility and profitability by implementing production technologies that are more common in mass-production (robots, flexible production systems, etc.). On the other hand, there is always lack of resources (human, financial, etc.). To escape this situation, the enterprise must use the right survival strategy: attaining the synergy in all its activities through the modularization of production systems and the accompanying information and knowledge management. It is shown that for production system decomposition, it is effective to divide the system into information and knowledge based modularized layers, which are related to the domains of product technology, production systems, jig development, etc. To demonstrate the results of the proposed approach, the case studies of planning three robot welding cells were analyzed.

Chaos control in multi-agent hierarchical systems discussed in Chapter 7 is a key issue at automated factories process design where human shortcomings may cause the cost rise of new factories about 5-10%. Wrong decisions made by the agents upper in the information flow may lead to the chaotic behaviour of downwards agents and therefore to the chaotic performance of the whole design and application system. The backbone of the present research is a unique advanced database covering the shortcomings analysis at the design and commissioning of 26 automated production plants all over the world. Further, a synergy-based preventive and active chaos control methodologies were developed according to the shortcomings trajectories and their combination with temporary management meta-structures. The further modelling of the matrix allows scheduling the activities and predicting the time required to complete certain tasks considering probable iterations and rework. As a case study, the two-stage methodology for a project duration prognosis is proposed based on discrete event modelling. It is proved that the proposed dynamical temporary meta-teams methodology realization is the key to empowering synergy in teamwork, which allows significant shortening of project implementation time - from 106.5% to 85.4%.

The overwhelming majority of the material in the present book has been published in a dispersed manner in over 60 publications in scientific journals and conference proceedings.

Now it is the time to argue about follow-up research in this book direction.

Proceeding from the title of the present book – Socio-Technical Synergetics the second part of this first compound word points to technology development. No doubt, it is a process lasting forever. But with the first part of this compound word, the situation is a little complicated. We have touched upon only a small part of social synergetics here – the human shortcomings as the reasoning of the "bad engineering". However, we could take a wider perspective as well, trying to construct foundations for a synergy-based dream society. The main obstacle on this track to synergistic society seems to be the most important law of nature – the Jungle Law, giving birth to extreme right and rabid societies. It urges the great powers to the major breakthrough in world governance. Perhaps it is appropriate here to remind the wording of the Jungle Law – the survival of the fittest, strongest or most cunning. It is also true that during the history, numerous attempts have been made to oppose this uncomfortable law. The fundamental importance in this direction was French Revolution, which inherited to us the three pillars of synergistic society: *liberty, equality, fraternity*. Unfortunately, later revolutions have not followed this tradition in full and we are witnesses of incomplete societies – autocracy and plutocracy. In the recent past, most close to the dream society has been the European welfare society.

Alas, we are witnesses of numerous wars all over of the world as proof of the monstrous rule of the Jungle Law. At the moment, the two Slavic nations in the middle of Europe are fighting for their living territory, killing each other with undisguised anger. In this barbaric and inhuman situation, it seems strange and unexpected to argue about synergy-based dream society. So I hope that the respected reader can forgive the absence of the last logical chapter in this book.

Vello Reedik
Tallinn, 2024

ABBREVIATIONS

AGREE - Advisory Group on Reliability of Electronic Equipment
APEX - Agile Project Management Execution
ASIC - Application-Specific Integrated Circuit
BPR - Business Process Re-Engineering
CAD - Computer-Aided Design
CDD - Clock Difference Diagrams
CFR - Constant Failure Rate
CI - Commonality Index
CNC - Computer Numerical Control
COTS - Commercial Off-The-Shelf
CPS - Cyber-Physical Systems
DAAAM - Danube Adrian Association for Automation & Manufacturing
DCS - Distributed Control System
DFQ - Design for Quality
DFRA - Decreasing Failure Rate Average
DM - Data Mining
DPMO - Defects per One Million Opportunities
DSM - Design (Dependency) Structure Matrix
EAS - Enterprise Estonia
ESFOT - Expected Service Free Operation Time.
EVM - Earned Value Management
FAC - Factory Automation Commissioning
FAD - Factory Automation Design
FAT - Factory Acceptance Test
FFDD - Fast Feedback Dependability Database
FRACAS - Failure Reporting and Corrective Action System
GMAW - Gas Metal Arc Welding
HAZOP - Hazard and Operability Study
HMI - Human Machine Interface
IC – Integrated Circuit
ICED- International Conference on Engineering Design
IFRA - Increasing Failure Rate Average
IIoT - Industrial Internet of Things
IMECC - Innovative Manufacturing Engineering Systems Competence Centre
IO - Input and Output
ISO - International Organization for Standardization
JOT – Just-On-Time
KISS - Keep It Short and Simple
LCA - Life-Cycle Analysis
LF - Light Fittings

LHS - Latin Hypercube Sampling
MAG - Metal Active Gas
MAS - Multi-Agent Systems
MC - Model Checking
MEMS - Micro-Electro-Mechanical Systems
MIG - Metal Inert Gas
MIM - Module Indication Matrix
MPC - Model Predictive Control
MT - Mature Technology
MTBF - Mean Time Between Failures
MTTR - Mean Time to Repair.
NT - New Technology
OE - Office Equipment
OGY - Ott, Grebogi, Yorke (Chaos Control Methodology)
PC - Personal Computer
PCB - Printed Circuit Board
PLCI - Product Line Commonality Index
PD - Product Development
PDF - Probability Density Function
PDP - Product Development Preparation
PDRM - Product Design and Resource Management
PID - Proportional, Integrative and Derivative
PRA - Product Realization and Analysis
PLC - Programmable Logic Controller
PLM - Product Lifecycle Management
PPF - Proportional Perturbations Feedback
PRA - Product Realization and its Analysis
QCC - Quality Control Circles
QFD - Quality Function Deployment
RF - Radio Frequency
RFID - Radio Frequency Identification
ROI - Return On Investment
ROM - Read Only Memory
RTU - Remote Terminal Unit
SAT - Site Acceptance Test
SCADA - Supervisory Control and Data Aquisition
SIL - Safety Integrity Level
SIM - Subscriber Identity Module
SIT - Site Integration Test
SME - Small and Medium-Sized Enterprises
SPC - Statistical Process Control
STS - Social-Technological Systems
SWOT - Strengths-Weaknesses-Opportunities-Threats Analysis

TDD - Theory of Design Domains
TOC - Theory of Constraints
TPM - Total Productive Maintenance
TQM - Total Quality Management
VDI - Verein Deutscher Ingenieure (German Engineering Society)

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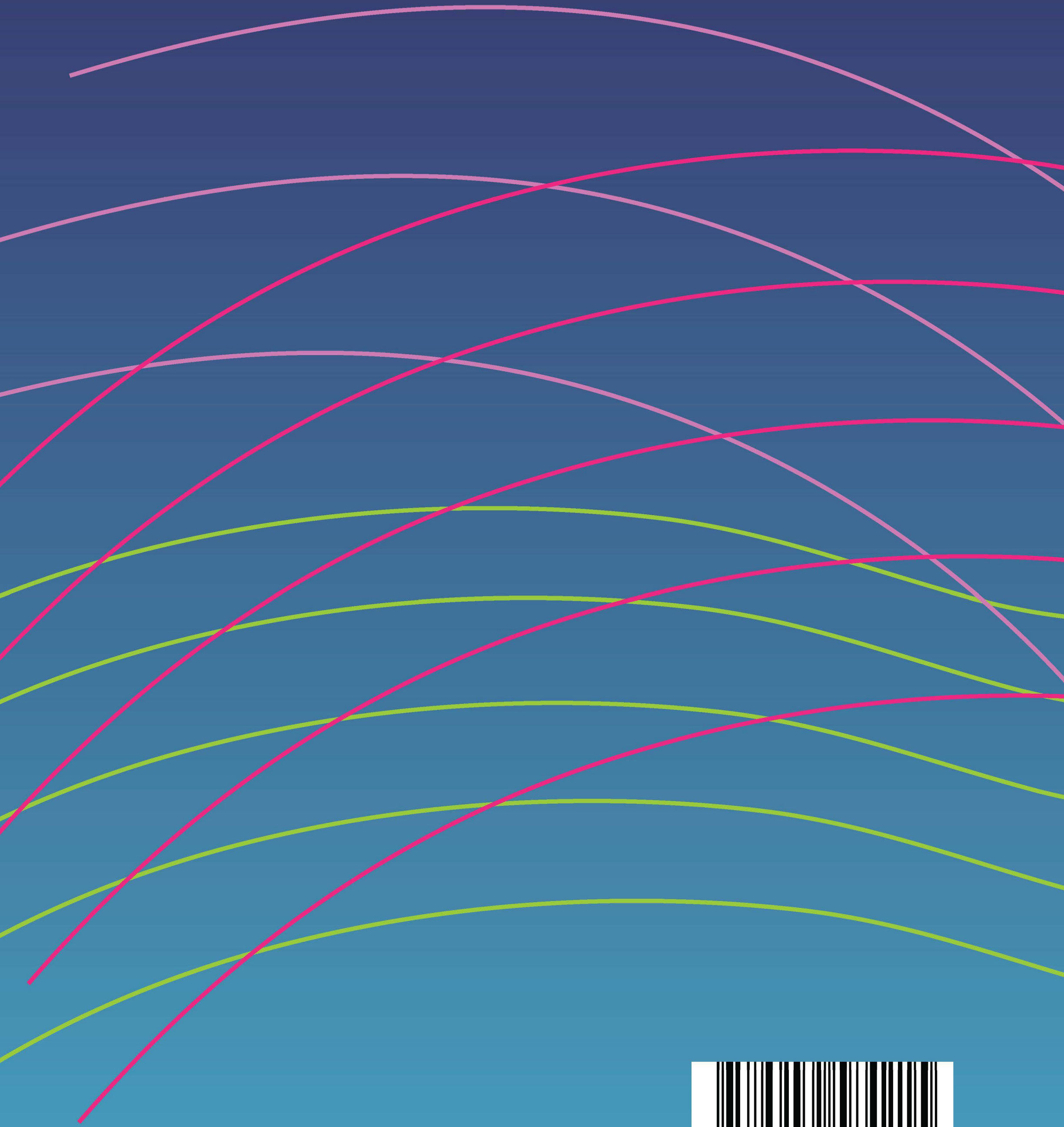

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