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Synergy-Based Approach to Quality Assurance

TIIT HINDREUS

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Faculty of Mechanical Engineering
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Declaration:

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

Tiit Hindreus

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ABBREVIATIONS

BPR	- Business Process Re-Engineering
DAAAM	- Danube Adria Association for Automation & Manufacturing
DFQ	- Design for Quality
DPMO	- Defects per One Million Opportunities
DSM	- Dependency Structure Matrix
FAC	- Factory Automation Commissioning
FAD	- Factory Automation Design
FAT	- Factory Acceptance Test
ICED	- International Conference on Engineering Design
ISO	- International Organization for Standardization
KISS	- Keep It Short and Simple
LF	- Light Fittings
LHS	- Latin Hypercube Sampling
MT	- Mature Technology
NT	- New Technology
OE	- Office Equipment
PDF	- Probability Density Function
PDP	- Product Development Preparation
PDRM	- Product Design and Resource Management
PRA	- Product Realization and its Analysis
QCC	- Quality Control Circles
QFD	- Quality Function Deployment
SPC	- Statistical Process Control
TDD	- Theory of Design Domains
TOC	- Theory of Constraints
TPM	- Total Productive Maintenance
TQM	- Total Quality Management

SYMBOLS

Symbol	Unit	Comment
a		Distribution minimum
b		Most likely distribution value
c		Distribution maximum
$E(x)$		Average value
$F(x)$		Cumulative distribution function
$f(x)$		Probability density function
F1		Faults due to misunderstandings in communication
F2		Faults due to negligence
$(L_{\max})_i$	%	Minimum percentage of original duration
$(L_{\text{ori}})_i$	%	Percentage of original duration
M1		Mistakes due to lack of competence
M2		Mistakes due to unknown matters at the moment of design
$OA(i, j)$		Overlap amount
$OI(i, j)$		Overlap impact
$RI(i, j)$		Rework impact
$RP(i, j, r)$		Rework probability
T		Technical shortcomings
$V(x)$		Dispersion

INTRODUCTION

Background to the research

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, property, value, goodness, etc. In the modern society the use of the concept of quality is still remarkably evolving and nowadays we talk self-evidently about the quality of life, emotions, environment, education, service, etc. In the present thesis the research area is delimited to the concept of product development and its quality assurance. The main difficulties which arise while defining the quality of the product are associated with the matter that it is at the same time a technical, perceptual and also a market-driven concept.

The technical side of product quality continues to be a key driver of the product development process and more attention is paid to improving the upstream activities of the product development process to ensure that quality is built in the product from the very beginning. Probably the most comprehensive analysis of how quality should be designed into products is comprised in the concepts of Design for Quality (DFQ) and Quality Function Deployment (QFD). The quality paradigm is widening on the customer side and dealing with “perception”, “value”, “feeling” and “mind-set” has become a modern field of research activities. Concepts such as globalization, mass customization, product branding, e-commerce suggest that product quality paradigm is still in evolvement (Robotham and Guldbrandsen, 2000). It is obvious that maximum quality would be attained in safety-critical systems, like space, nuclear and military technology, but the cost of these products is an order higher than that of the same purpose consumer goods. In order to achieve 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. So, quality and reliability characteristics for non-safety-critical products have always been market-driven. Everything mentioned above is concentrated only on the product quality concept, which is a substantial precondition for successful business. Historically there exist a lot of concepts and systems for improving the quality of business which form a common notion called quality management systems. The beginning of the development of quality management systems may be associated with emerging mass production where the production was divided between different teams working at specific stages of production.

The Quality Departments were introduced to oversee the quality of production and ratifying the errors (Taylor, 1911). Probably the first quality management principle was 14 Points for Management (Deming, 1986). Quality as a profession and a managerial process was introduced during the second half of the 20th century being an emerging field in the 1990s.

All the developments described above have resulted in establishing the ISO9000 standard series on quality management systems by the International Organization for Standardization (ISO). 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 (Oakland, 1989). There is a strong belief among the managers that Total Quality Management (TQM) and ISO9000 standard series take a good care of quality. This view is supported by testified benefits of TQM investments gained by quality award winners (Singhal, 2003).

All popular quality management systems such as Hoshin Kanri, Zero Defects, Theory of Constraints (TOC), Six Sigma, Kaizen, TQM, Balanced Scorecard, etc. are focussed on business and management quality of companies. These quality management concepts naturally also include product design quality as a concept but in reality they are still somewhat disunited. Attempts have been made to integrate them closer, from which the most noted are the concepts of Design for Quality (Mørup, 1993), further developments of Quality Function Deployment (Akao, 1994) and some others, all of which suffer from the lack of a suitable integrating basis. This circumstance serves as a springboard for the present doctoral research. Obviously, for this integration a meta-approach is necessary and the present doctoral thesis attempts to solve this problem. As the research team has experience in developing synergy-based design methodology, it is quite natural to try to enlarge this approach also to quality management systems.

Research methods and positioning

The increase of the integration of different technologies in new products with better performance and marketing power due to the exploitation of the best features of allied technologies has been an ever-growing quality driver during the last decades. It is obvious that in this interdisciplinary mix there is “something” more than these technologies offer alone, for example, the realization of the functions not existing before, increase of flexibility both during design and use (multifunctional ability), compensation of mutual weaknesses (synergy), physical integration, etc. At the same time, the design of interdisciplinary systems integrating different technologies is a very complicated task and the result of this integration depends mainly on the quality of engineering. For a long time it has been hoped that it is possible to compensate and overcome shortcomings in engineering design by planting strict prescriptive design methodologies. Around the beginning of the present century the engineering design research community reached the somewhat confusing conviction that engineering design is not a pure technical problem any more but a complex activity, involving artefacts, people, tools, processes, organisations and conditions of the real economic environment (Blessing, 2003; Hansen and Andreasen, 2003; Persson et al., 2003). Depending on the above-

described change of the engineering design paradigm a new wave of research into human aspects in engineering design activities can be noticed.

In the launched race between research groups to fill the gap in the area of engineering design methodologies the present research team has contributed (with) a new paradigm – the synergy-based approach to design (Kaljas and Reedik, 2005). The synergy-based approach to the design of interdisciplinary systems based on the compensation of mutual weaknesses and amplification of useful effects between the allied technologies seems to be a good possibility to solve the problem also in quality context. Synergy defines the situation where the summary effect at the integration of different technologies is greater than their sum. The synergy-based approach has been successfully used in business theory, medicine and for training in sport. The synergy-based approach to the design of interdisciplinary systems was initiated at the Department of Machinery of Tallinn University of Technology (TUT) by Prof. V. Reedik. For the first time the synergy-based approach to the design of mechatronic systems was presented on international research forums in 1998 (Tähemaa and Reedik, 1998; Kaljas and Reedik, 1998). However, the synergy-based physical and logical optimization principles were used already in the late 60s in the studies of high-accuracy pneumatic interruptible jet sensors and in the development of a high-performance pneumo-hydraulic relay servo. The synergy-based approach makes it possible to bring design parameters, market conditions, human factors, reliability problems, etc. under one umbrella.

In Figure 0.1 it is shown how the present research is positioned among the latest research efforts of the team. The doctoral study of T. Tähemaa (Tähemaa, 2002), was a substantial step on synergy-based approach to engineering design. He analyzed an extensive database of the shortcomings of mechatronic office equipment in the service area and proved the reality of the positive and negative synergy concepts. This research gave evidence that the quality of engineering depends on the synergy of the activities of product development team members, resulting in a successful or failed product. The last possibility can be characterised by the term “bad” engineering. This was a starting point for the doctoral studies of F. Kaljas (Kaljas, 2005) which provided a deep research into human shortcomings at equipment control and the design and commissioning of factory automation systems. Afterwards F. Kaljas developed a framework for the synergy-based design of interdisciplinary systems. By integrating the Dependency Structure Matrix (DSM) technology and the Theory of Design Domains (TDD) he has reached a novel generic environment for the design of interdisciplinary systems on the border of prescriptive and descriptive design environments. It was shown that in the above-mentioned environment it is possible to develop a category of adaptive design tools allowing to synthesise decision-making algorithm depending on the competence of the design team.

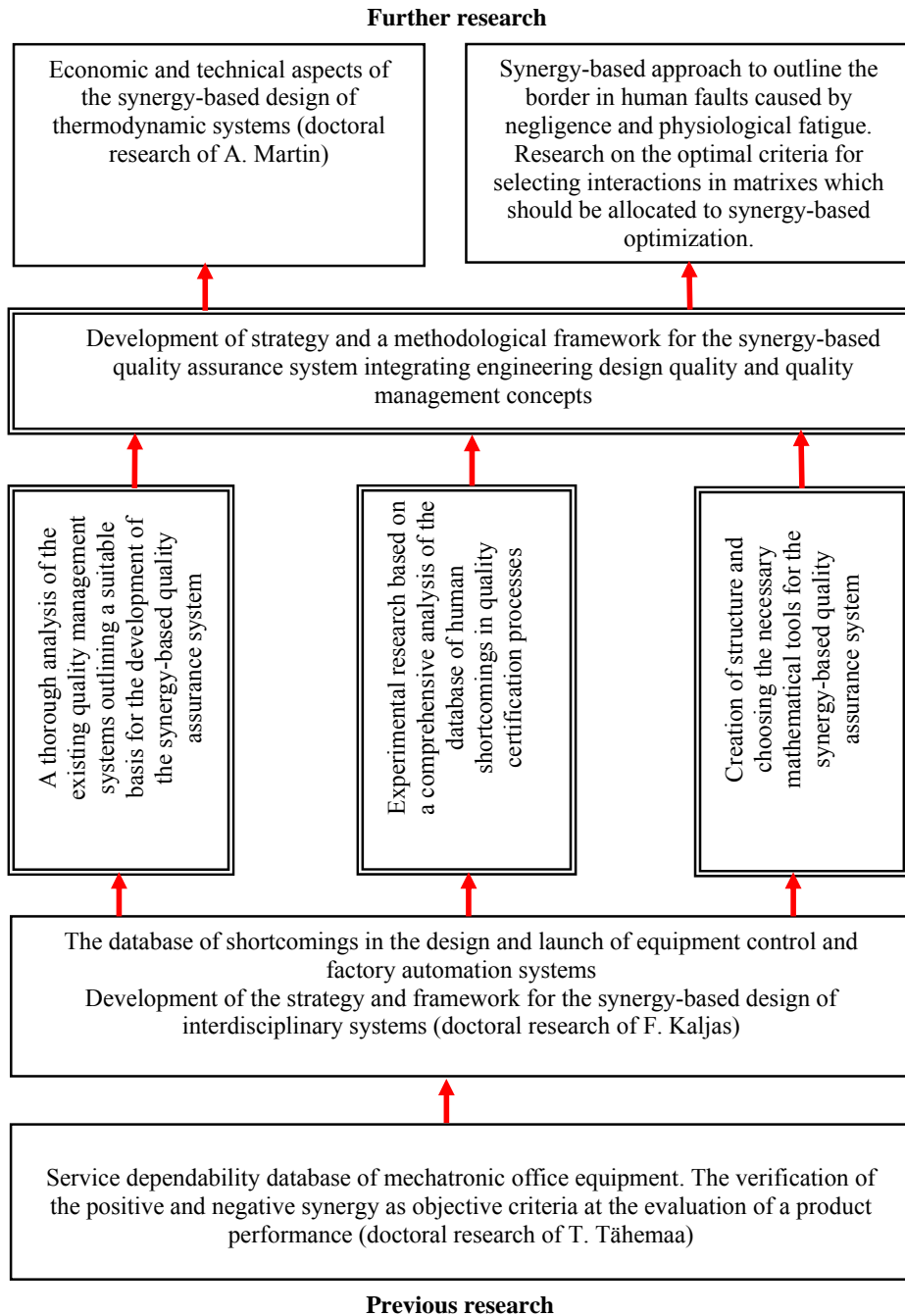


Figure 0.1 Generic structure of the present thesis (double-line boxes)

The present doctoral research is not a separate study but rather an independent part of the activities of a larger research group (see Figure 0.1). A detailed analysis of the objective and tasks of the thesis in the described framework is given in the next part of the introduction.

Research objective and tasks

The objective of the present research is to develop a synergy-based framework for quality management integrating it with the concept of engineering design quality into an overall effective quality assurance system.

To attain this objective, five basic tasks have to be solved:

- 1) to provide a thorough analysis of the existing quality management systems to outline a suitable basis for their integration with the concept of product quality;
- 2) to conduct experimental research based on a comprehensive analysis of the database of human shortcomings perceived during the certification of quality management systems and to transfer the results into synergy context;
- 3) to create structure and choose the necessary mathematical tools able to support the built in quality at product development and empower quality management activities;
- 4) to develop a strategy and a methodological framework for synergy-based quality management systems;
- 5) to create a synergy-based framework for integrating the concepts of quality management and product quality, capable of supporting companies while preparing for the certification of their quality management system.

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

The first task, traditional for any scientific investigation, is to form a clear vision of the state of the art in the field of research. Therefore, first of all, it is necessary to study the existing quality management systems and evaluate their potential to manage the complicated tasks of assuring the quality and competitiveness of the developed products. During the analysis of the existing knowledge and experience it is possible to benchmark the contribution of the doctoral research against the overall picture.

The second research task involves the complicated task of studying the reasons for “bad” engineering, separating human shortcomings in engineering and quality management activities from technical reasons. It means that, first of all, the previously completed databases of human shortcomings must be reevaluated. However, at the same time it is necessary to complete a large database of human mistakes and faults noticed during the certification of quality management systems of producing companies. The latter provides a firm basis for initiating and verifying the results of the present doctoral research.

The third task is to build up a basic framework for quality assurance systems, able to support the synergy-based integration of the concepts of quality management and engineering design quality. First, it is necessary to find effective information handling systems which can support the quality concept of the synergy-based integration of different technologies. Secondly, it is necessary to find a meta-approach to support the time- and task-dependent product development and quality management. For all of these activities it is necessary to choose suitable mathematical tools for the prognosis of the timing of quality assurance processes.

The fourth task presumes comprehension of the basic matters of the synergy-based approach to quality management systems. First of all, due to the findings of the present research the philosophy of synergy-based optimization and conception of human shortcomings needs reshaping. Secondly, it is necessary to add the finishing touches to the synergy-based engineering design methodology, testing it for development the light fittings in real industrial conditions. After that it is possible to start the outlining of the synergy-based quality management system. The last task is to summarize the outcome of the solutions of the previous tasks in order to propose a complete framework for quality assurance by synergy-based integration of the concepts of engineering design quality and quality management. After that it is possible to build up a novel framework for the quality assurance system, able to cover all aspects of the product development process and product realization activities resulting in a suitable tool for the preparation of a company's management system for quality certification.

The present doctoral research may tend to be superficial and diffusive, thus distancing from the classical strict structure of a thesis. However, the integrated topics described above emphasize the generalistic pattern of this thesis. By and large, the research is based on a unique database of human shortcomings compiled in the framework of the research. In fact, all the above mentioned determined the structure of the thesis (see Figure 0.1) and ensures that the value of the findings is verified and trustworthy.

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1 ANALYSIS OF QUALITY MANAGEMENT SYSTEMS

1.1 Milestones of stepping up quality thinking

Quality thinking has surrounded humanity from the beginning of times and this was a long time before the Latin word *quālitās* was taken into use. Not only did primeval humans carefully follow the performance quality of their arms 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 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 who officially proclaimed the law on human actions quality (King, 2005).

The concept of quality as we think of it now first emerged during the Industrial Revolution. Previously goods had been made by hand and from start to finish by the same person or team of people, tweaking the product to meet quality criteria. Mass production brought huge teams of people together to work in specific stages of production where one person would not necessarily complete a product from start to finish and problems of responsibility for the final quality of the product cropped up. So, in the late 1800s pioneers such as F. W. Taylor and H. Ford recognized the limitations of the methods being used in mass production at the 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 component standards to ensure a standard product was produced (Ford and Crowter, 1922). In these times management of quality was the responsibility of the Quality Department 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 produced his 14 Points for Management (Deming, 1986), in order to help people understand and implement the necessity of transformation. They apply to both small and large organizations, and to service industries as well as to manufacturing. Quality, as a profession and the managerial process associated with the quality function, was introduced during the second-half of the 20th century. Over this period, few other disciplines have seen as many changes as the quality profession. The quality profession grew from simple control to the field of systems engineering.

Table 1.1 defines quality from the view point of different quality professionals and all this can be classified into three sections. As one can see the meaning of the term quality has developed over time. In summary quality can be interpreted as "Customer's expressed and implied requirements are met fully". It is important to note that satisfying the customers' needs and expectations is the main factor in all these definitions. Therefore it is an imperative for a company to identify such needs early in the product/service development cycle. The ability to define accurately the

needs related to design, performance, price, safety, delivery, and other business activities and processes will place a firm ahead of its competitors on the market. Quality in everyday life and business, engineering and manufacturing has a pragmatic interpretation as the *non-inferiority*, *superiority* or *usefulness* of something. Some Japanese companies find that "conformance to a standard" too narrowly reflects the actual meaning of quality and consequently have started to use a newer definition of quality as "providing extraordinary customer satisfaction".

Table 1.1 Quality definitions from the view point of different quality professionals

Customer-based definitions	
Kano, 1984	Products and services that meet or exceed customers' expectations
Juran, 1988	Quality is fitness for use
Oakland, 1989	The core of a total quality approach is to identify and meet the requirements of both internal and external customers
Manufacturing & service-based definitions	
Crosby, 1979	Do it right first time
Value-based definitions	
Feigenbaum, 1951	Quality is the degree to which a specific product conforms to a design or specification
Deming, 1986	Better quality at lower price has a chance to capture a market. Cutting costs without improvement of quality is futile
ISO 9000:2000	Degree to which a set of inherent characteristics fulfills requirements

In the modern manufacturing industry it is commonly stated that "Quality drives productivity." Improved productivity is a source of greater revenues, employment opportunities and technological advances. Most discussions of quality refer to a finished part, wherever it is in the process. Inspection, which is what quality insurance usually means, is historical, since the work is done. The best way to think about quality is in process control. If the process is under control, inspection is not necessary. In the past, when we tried to improve quality, typically defined as producing fewer defective parts, we did so at the expense of increased cost, increased task time, longer cycle time, etc. However, when modern quality techniques are applied correctly to business, engineering, manufacturing or assembly processes, all aspects of quality - customer satisfaction and fewer defects/errors and cycle time and task time/productivity and total cost, etc.- must improve or, if one of these aspects does not improve, it must at least stay stable and not decline.

The most progressive view of quality seems to be that it is defined entirely by the customer or end user and is based upon that person's evaluation of his or her entire customer experience. The customer experience is the aggregate of all the touch points that customers have with the company's product and services, and is by definition a combination of these. For example, any time one buys a product one forms an impression based on how it was sold, how it was delivered, how it performed, how well it was supported etc.

1.2 Dynamics in the development of quality standards

The history of quality standards goes back to ancient times. The Code of Hammurabi (Codex Hammurabi), the best preserved ancient law code, was created ca. 1760 BC in ancient Babylon. Hammurabi had the laws inscribed in stone, so they were immutable. In the law we can find interesting clauses, for instance clause number 229 states "If a builder build a house for someone, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death" (King, 2005). That statement is the reason why the houses built around 2000 years BC are still in use.

During the Second World War, there were quality problems in many British industries such as ammunition industry, where bombs were exploding in factories during assembly. The adopted solution was to require 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 specified not what to manufacture, but how the manufacturing process was to be managed. In 1987, the British Government persuaded the International Organization for Standardization to adopt BS 5750 as an international standard and BS 5750 became ISO 9000 (Seddon, 2000a). ISO 9000 is a family of standards for quality management systems. ISO 9000 is maintained by the International Organization for Standardization and is administered by accreditation and certification bodies.

ISO 9000:1987 had the same structure as the UK Standard BS 5750, with three models for quality management systems, the selection of which was based on the scope of activities of the organization:

- ISO 9001:1987 Model for quality assurance in design, development, production, installation, and servicing for companies and organizations whose activities included the creation of new products.
- ISO 9002:1987 Model for quality assurance in production, installation, and servicing had basically the same material as ISO 9001 but without covering the creation of new products.
- ISO 9003:1987 Model for quality assurance in final inspection and test covered only the final inspection of the finished product, with no concern for how the product was produced.

ISO 9000:1987 was also influenced by existing US and other Defense Standards ("MIL SPECS"), and so was well-suited to manufacturing. The emphasis tended to be placed on conformance with procedures rather than the overall process of management - which was likely the actual intent.

ISO 9000:1994 emphasized quality assurance via preventative actions, instead of just checking the final product, and continued to require evidence of compliance with documented procedures. As with the first edition, the down-side was that companies tended to implement its requirements by creating shelf-loads of procedure manuals, and becoming burdened with an ISO bureaucracy. In some companies, adapting and improving processes could actually be impeded by the quality system.

ISO 9001:2000 combines the three standards 9001, 9002, and 9003 into one, now called 9001. Design and development procedures are required only if a company does in fact engage in the creation of new products. The 2000 version sought to make a radical change in thinking by actually placing the concept of process management to the front. The 2000 version also demands involvement of upper executives, in order to integrate quality into the business and avoid delegation of quality functions to junior administrators. Another goal is to improve effectiveness via process performance metrics - numerical measurement of the effectiveness of tasks and activities. Expectations of continual process improvement and tracking customer satisfaction were made explicit.

TC 176, the ISO 9001 technical committee, reviewed the next version of ISO 9001, which is termed the ISO 9001:2008 standard and was released on 15 November 2008. The standard was not substantially changed compared to the 2000 version.

A company or organization that has been independently audited and certified to be in conformance with ISO 9001 may publicly state that it is "ISO 9001 certified" or "ISO 9001 registered". ISO 9001 certification does not guarantee that the company delivers products of superior (or even decent) quality. It just certifies that the company engages internally in paperwork prescribed by the standard. Indeed, some companies enter the ISO 9001 certification as a marketing tool.

1.3 Economics of quality assurance

Before specifying the tasks of the present research it is necessary to achieve clarity in the debates on the real effectiveness of quality certification. It is necessary to make clear if quality assurance systems are an interesting playground or how their implementation supports a solid economic outcome. This has been the subject of numerous discussions and to some extent it provides a background to the better focusing of the present research. The debate on the effectiveness of ISO 9001 commonly centers on the following questions: Are the quality principles in ISO 9001:2000 of value? Does it help to implement an ISO 9001 compliant quality management system? Does it help to obtain ISO 9001 certification?

In the 1990s there was an acute dispute in business media over the weak impact of total quality management (TQM) on the financial performance of enterprises (Singhal, 2003). Is the TQM a management paradigm based on total customer satisfaction, employee involvement and long-term partnership with suppliers/customers really able to improve the financial performance of enterprises or is it a fad? Is the TQM still strong in competition with other paradigms like re-engineering, customer-centred organisations, process-oriented organisations, learning organisations, supply-chain management or are these new trends in a way offsprings of TQM philosophy?

The analysis provided by Singhal (Singhal, 2003) is based on the evaluation of TQM investments benefit based on 600 quality award winners in the USA. They were compared with the firms of the similar size from the same industry and it gave a positive answer. It is proved that quality award winners outperformed the benchmarks on almost every performance measure. The indicators like the growth of operative income, sales growth, total assets, number of employees and also the efficiency of return on sales and assets have made a good progress. It is interesting that low capital-intensive firms have more opportunities for gains from TQM activities than capital-intensive firms. It is somewhat surprising that smaller firms have potential to get more profit from TQM than larger firms. However, a broad statistical study of 800 Spanish companies (Dalglish, 2005) found that ISO registration in itself creates little improvement because companies interested in ISO have usually already made some type of commitment to quality and were performing just as well before registration. In today's economy, more and more companies are using ISO 9001 as a business tool. Through the use of properly stated quality objectives, customer satisfaction surveys and a well-defined continual improvement program companies are using ISO 9001 processes to increase their efficiency and profitability.

A common criticism of ISO 9001 is the amount of money, time and paperwork required for certification (Clifford, 2005). Opponents believe that if a company has documented its quality systems, then most of the paperwork has already been completed (Barnes, 2000). According to Seddon (Seddon, 2000b), ISO 9001 promotes specification, control, and procedures rather than understanding and improvement. Wade (Wade, 2002) argues that ISO 9000 is effective as a guideline, but that promoting it as a standard helps to mislead companies into thinking that certification means better quality. However, the need for an organization to set its own quality standards is still present. Paraphrased, Wade's argument is that total, blind reliance on the specifications of ISO 9001 does not guarantee the development of a successful quality system. Certifications are in fact often based on customer contractual requirements rather than a desire to actually improve quality (Barnes, 2000; Henricks, 2001). Certification by an independent auditor is often seen as the problem area, and according to Barnes, has become a vehicle to increase consulting services (Barnes, 2000). In fact, ISO itself advises that ISO 9001 can be implemented without certification, simply for the quality benefits that can be achieved (The ISO Survey, 2005). A serious problem reported is the

competition among the numerous certifying bodies, leading to a softer approach to the defects noticed in the operation of the Quality System of a firm. The question is if certification itself is important to the marketing plans of the company. If it is not, do not rush to certification. Even without certification, companies should utilize the ISO 9000 model as a benchmark to assess the adequacy of its quality programs.

In summary 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 (Dalglish, 2005; Barnes, 2000). The quality principles in ISO 9000:2000 are also sound, according to Wade, (Wade 2002) and Barnes, (Barnes, 2000) as they provide a comprehensive model for quality management systems that can make any company competitive. Barnes also cites a survey by Lloyd's Register Quality Assurance which indicated that ISO 9000 increased net profit, and another by Deloitte-Touche which reported that the costs of registration were recovered in three years. According to the Providence Business News (Providence, 2000), implementing ISO often gives the following advantages: creates a more efficient, effective operation, increases customer satisfaction and retention, enhances marketing, improves employee motivation, promotes international trade, increases profit, reduces waste and increases productivity.

1.4 Organizational dimensions of quality management and the evaluation of the possibilities of its integration with the concept of product quality

During the previous research the present team has experienced that possibility to build quality in the product from the first steps of product development depends mostly on the quality of engineering design (Kaljas, 2005). The basic idea of the present research is to propose a novel approach to the integration of the so far disunited assurance of product technical or performance quality and a company's quality management into one effective quality assurance framework. It is necessary to underline that this integration has been a natural target of any quality management system. So it is necessary to find a quality management system which could be used for the integration with the concept of product quality. It is obvious that for this integration it is also necessary to find a metatool fitting for both systems. From the point of view of product quality the synergy-based approach has recommended itself as the best available metatool.

Many different techniques and concepts have been evolved to improve product, production and service quality, including SPC, Quality Function Deployment (QFD), Hoshin Kanri, Zero Defects, Theory of Constraints (TOC), Six Sigma, Kaizen, Total Quality Management (TQM) and Balanced Scorecard etc.

Statistical Process Control (SPC) was pioneered by Walter A. Shewhart in the early 1920s. Statistical Process Control is an effective method of monitoring a process through the use of control charts. By collecting data from samples at

various points within the process, variations in the process that may affect the quality of the end product or service can be detected and corrected. Control charts enable the use of objective criteria for distinguishing background variation from events of significance based on statistical techniques (Roberts, 2005). W. Edwards Deming later applied SPC methods in the United States during World War II, thereby successfully improving quality in the manufacture of munitions and other strategically important products. Deming is also known as the introducer of SPC methods to Japanese industry after the war had ended.

Quality Function Deployment (QFD) was originally developed by Yoji Akao in 1966 when the author combined his work in quality assurance and quality control with function deployment used in Value Engineering (Akao, 1994). Akao described QFD as a “method to transform user demands into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process”. QFD is designed to help planners focus on characteristics of a new or existing product or service from the viewpoints of market segments, company, or technology-development needs. The technique yields graphs and matrices. QFD is applied in a wide variety of services, consumer products, military needs and emerging technology products. The technique is also used to identify and document competitive marketing strategies and tactics. QFD is considered a key practice of Design for Six Sigma. It is also implicated in the ISO 9000:2001 standard which focuses on customer satisfaction. Results of QFD have been applied in Japan and elsewhere into deploying the high-impact controllable factors in strategic planning and strategic management (also known as Hoshin Kanri, Hoshin Planning or Policy Deployment). Hoshin Planning or *hoshin kanri*, an organization-wide strategic planning system, has been widely used in Japanese companies since 1975 (King, 1989). Both methods seek breakthrough performance, alignment, and integrated targets for all levels.

During the 1990s, large companies in the automotive industry tried to cut costs by reducing their quality inspection processes and demanding that their suppliers dramatically improve the quality. This eventually resulted in demands for the "Zero Defects" standard which is implemented all over the world (Crosby, 1979). Although applicable to any type of enterprise, it has been primarily adopted within industry supply chains wherever large volumes of components are being purchased (common items such as nuts and bolts are good examples).

Theory of Constraints (TOC) is an overall management philosophy introduced by E. M. Goldratt (Goldratt, 1984). It is based on the application of scientific principles and logic reasoning to guide human-based organizations. There is not so much connection to product quality as the management theory is of the first priority.

In 1986, B. Smith, a senior engineer and scientist at Motorola, introduced the concept of Six Sigma to standardize the way how defects are counted. The term "Sigma" is often used as a scale for levels of "goodness" or quality. Using this scale, "Six Sigma" equates to 3.4 defects per one million opportunities (DPMO).

Six Sigma is a business improvement methodology that focuses an organization on understanding and managing customer requirements, aligning key business processes to achieve those requirements, utilizing rigorous data analysis to minimize variation in those processes, driving rapid and sustainable improvement to business processes. The Six Sigma Management System drives clarity around the business strategy and the metrics that most reflect success with that strategy. It provides the framework to prioritize resources for projects that will improve the metrics, and it leverages leaders who will make efforts for rapid, sustainable, and improved business results. Six Sigma Quality is a movement that inherits directly from TQM, (Total Quality Management). It uses much the same toolset and the same concepts.

Kaizen is often translated in the West as ongoing, continuous improvement. Some authors explain Japan's competitive success in the world market as the result of the implementation of the Kaizen concept in Japanese corporations. In contrast to the usual emphasis on revolutionary, innovative change on an occasional basis, Kaizen looks for uninterrupted, ongoing incremental change. Originally a Buddhist term, Kaizen comes from the words "Renew the heart and make it good." According to Imai (Imai, 1986), Kaizen means improvement but moreover it means continuing improvement in personal life, home life, social life, and working life. When applied to the workplace Kaizen means continuing improvement involving everyone - managers and workers alike. Support throughout the entire structure is necessary to become successful at developing a strong Kaizen approach. Management as well as workers need to believe in the Kaizen idea and strive toward obtaining the small goals in order to reach overall success. Kaizen is mainly a philosophical method and there is no connection to product design itself but it is very close to the synergy-based approach to human aspects in overall quality.

One of the latest well-known modern management methodologies is the Balanced Scorecard, a management concept introduced by Kaplan and Norton, which helps managers at all levels monitor results in their key areas (Kaplan and Norton, 1992). What is new is that Kaplan and Norton have recommended broadening the scope of the measures to include four areas: financial performance, customer knowledge, internal business processes, learning and growth. This allows the monitoring of present performance, but also tries to capture information about how well the organization is positioned to perform well in the future. Kaplan and Norton cite the following benefits of using the Balanced Scorecard: focusing the whole organization on the few key things needed to create breakthrough performance, helping to integrate various corporate programs, such as quality, re-engineering, and customer service initiatives, breaking down strategic measures to local levels so that unit managers, operators, and employees can see what is required at their level to roll into excellent performance overall. The Balanced Scorecard is basically a management tool.

To summarize, it is evident that to achieve excellence, companies must develop a corporate culture of treating people as their most important asset and provide a

consistent level of high quality products and services in every market in which they operate. Such an environment has supported the wide acceptance of Total Quality Management (TQM) which emerged as a new, challenging, marketable philosophy. It involves three spheres of changes in an organisation - people, technology and structure. There is also a need for a systematic approach so that each element of TQM can be bonded together smoothly. Oakland (Oakland, 1989) originated the idea of a 3-cornerstone model. In addition, the proposed 4-pillar model (see Figure 1.1) brings the customer's requirements into the system (Ho, 1999) and makes the approach to TQM more complete. The additional pillar “satisfying customers” is vital because it explicitly addresses the customer’s requirements and without it TQM would have no objective.

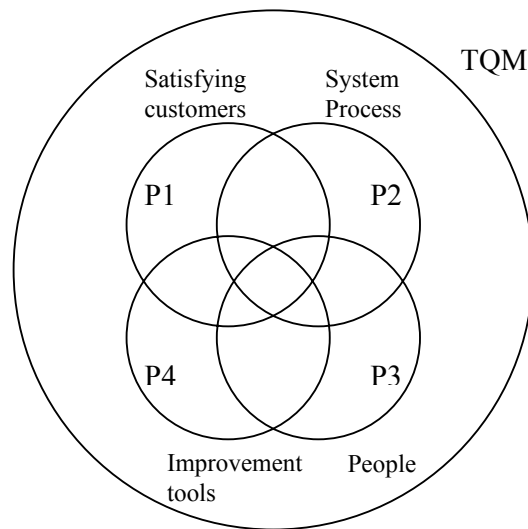


Figure 1.1 The Four Pillars of TQM (Ho, 1999)

The role of top management in the implementation of total quality is crucial and its input on people far-reaching. TQM, therefore, 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. The idea was to develop a universally applicable step-by-step guideline by including recognized practices in TQM: Japanese 5-S Practice (5-S), Business Process Re-engineering (BPR), Quality Control Circles (QCCs), ISO 9001 Quality Management System (ISO) and Total Productive Maintenance (TPM). 5-S is the key to total quality environment and therefore, it should be the first step. BPR is concerned with re-defining and designing of the business process in order to meet the needs of customers effectively. It is more concerned with the business objectives and systems, and should follow as Step 2. QCCs are concerned

with encouraging the employees to participate in continuous improvement and guide them through. Therefore, this should be Step 3. ISO 9000 (Step 4) is to develop a quality management system based on the good practices in the previous three steps. TPM is a result of applying 5-S to equipment based on a sound quality management system. In fact ISO 9001 requires procedures for process control and inspection and testing equipment which are part of TPM. Therefore TPM should be implemented in Step 5.

If the above five steps have been implemented successfully, the organization is already very close towards achieving TQM. TQM is a sequential model which is easy to remember and simple to implement. This is in line with the quality principle of Keep It Short and Simple (KISS), although it is not simple to make a model simple! Companies starting to implement TQM should follow TQM step-by-step. TQM philosophy is touching all activities of the organization. Product quality itself is one but not the main focus of TQM. The philosophy sees that if all other elements ranging from customer requirements to production control are controlled, the product quality is guaranteed. In reality the product's performance quality should be especially focused on in order to ensure a product which satisfies the customer and it seems that this philosophy is a suitable partner to the synergy-based approach.

In summary, the picture described above is multicoloured and it is difficult to differentiate between the borders of the intertwined approaches. However, in this multiplicity it seems that the TQM philosophy is the most suitable basis for the development of an integrated synergy-based quality assurance system. As one can see the integration of the concepts of product and quality management is used in every quality management system which differ only in emphasis and available tools. The most competitive ones for synergy-based integration are the different developments of QFD, Design for Quality systems and Kaizen approach. The four-phase QFD approach is based on the analysis of parametrical matrixes in order to translate customer needs to technical characteristics with following matrixes for process planning and quality control. This is a time- and stage-dependent system without a visible deeper integrating basis. Design for Quality (Mørup, 1993) is focussed on product design with emphasis on DFQ preconditions and extracting 8 elements of DFQ in the quality management scheme. This approach also suffers mainly from lack of an integrating metatool. 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 may be a suitable universal metatool for the closer integration of product quality and quality management systems.

1.5 Conclusions of Chapter 1

1. The quality of a product or service even more refers to the mix of perception and technical performance to which the product or service meets the customer's expectations. Quality has no specific meaning unless related to a specific function and/or object.
2. The standard ISO 9001 seems to take a good care of improving the business of the company, its sales growth and competitive advantage. Still, following the ISO 9001 standard recommendations does not guarantee the quality of product as it depends on the used design methodology and possibility to build the quality into the product during the whole product development and realization process.
3. On the basis of the economic analysis of quality certification it is possible to conclude that the profitable research in this area is reasonable. If the present research leads to completing a tool for the self-preparation of companies for certification, it is remarkable support for empowering the competitiveness of companies.
4. The multiplicity of quality management systems offers a wide choice of tools for continual improvement supported by quality thinking and quality assurance activities in the company. Despite everything, the key driver in the business of the company is still product quality which depends on the use of the most suitable design process and condenses teamwork abilities of the engineering staff throughout the product development and realization process.
5. It is obvious that the concepts of quality management and product quality seem to be somewhat departed in the common quality assurance environment. For their closer integration it is necessary to find a metatool of a higher level. The experience of the research team in the design of interdisciplinary systems has shown that a suitable integrating metatool may be found in the synergy based approach.

2 INVESTIGATION OF HUMAN SHORTCOMINGS DURING THE CERTIFICATION PROCESS OF QUALITY MANAGEMENT SYSTEMS

2.1 Overview of previous research into human shortcomings

The Industrial Revolution that started with the application of steam power and the creation of large factories in the late 18th century led to great changes in the production of textiles and other products. The factories that evolved created tremendous challenges to organization and management that had not been confronted before. Managing these new factories and later new entities like railroads with the requirement of managing large flows of material, people, and information over large distances created the need for some methods for dealing with the new management issues.

The most important of those who began to create a science of management was F. W. Taylor, (1856-1915). Taylor was one of the first to attempt to systematically analyze human behavior at work. Taylor attempted to apply to complex organizations what engineers had applied to machines and this involved turning individuals into the equivalent of machine parts. Just as machine parts were easily interchangeable, cheap, and passive, so should human parts be in the machine model of organizations (Taylor, 1911).

The minimization of human shortcomings involved breaking down each task into its smallest units and figuring out the best way to do each job. Taylor attempted to make a science for each element of work and restrict behavioral alternatives facing the worker. The overall goal was to remove human shortcomings and the results were profound. Under Taylorism productivity went up dramatically. New departments arose such as industrial engineering, personnel, and quality control. The core elements of Taylor's scientific management remain popular today and they have merely been modified and updated.

Despite the economic progress brought about in part by scientific management, critics were calling attention to the "seamy side of progress," which included severe labor/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. In addition, factors like World War I, developments in psychology (e.g. Freud) and later the depression, all brought some of the basic assumptions of the scientific management school into question.

The most famous of these studies was the Hawthorne studies which showed how work groups provide mutual support and effective resistance to management schemes to increase output. This study found that workers did not respond to classical motivational approaches as suggested in the Taylor's scientific management, but rather workers were also interested in the rewards and punishments of their own work group. These studies, conducted in the 1920s,

started as a straightforward attempt to determine the relationship between work environment and productivity. The results of the research led researchers to feel that they were dealing with socio-psychological factors that were not explained by the classic theory which stressed the formal organization and formal leadership. The Hawthorne studies helped us to see that an organization is more than a formal arrangement of functions but is also a social system. Later in the last century research into human behavior was focused on the psychology of work.

During all this time technologies have developed faster and faster and engineering work has become even more interdisciplinary in character. The increase of the integration of different technologies in new products with better functionality and marketing power has been an ever-growing tendency during the last decades. For a long time it has been hoped that it is possible to compensate and overcome shortcomings in engineering design by planting strict prescriptive design methodologies. However, some confusion can be noticed in the development of the comprehensive methodologies for interdisciplinary systems design as nowadays engineering design is not only a pure technical problem any more (Hansen and Andreasen 2003). Design is a complex activity, involving artefacts, people, tools, processes, organisations and the micro- and macroeconomic environment (market, legislation, society) in which it takes place (Blessing, 2003).

The ever-growing competition on the markets has caused the need for radical cuts in product development time and therefore more frequent renewal of product models. Therefore new products have to be developed in conditions of limited feedback information concerning the reliability and performance of previous products. That has put the industry into a difficult position and has forced it to change the design for quality and reliability paradigms. As a result, the influence of human factors on new product development quality is growing remarkably. However, there are still few and dispersed data available about the quantified influence of human shortcomings in the full-scale engineering activities from the early stages of design towards the application and follow-up product development. Depending on the above described change of the engineering design paradigm a new wave of research into human behaviour in engineering activities can be noticed.

The research team of Prof. V. Reedik at TUT, to which the author of the present thesis also belongs, started research into human shortcomings in the middle of the 90s. From the very beginning, the cornerstone of the research has been the proposal that “bad” engineering is mostly the result of communication disturbances between the members of the design team, persons’ competence level and physiological condition. The driving force of the research team was to find an effective approach to fighting against the so-called “bad engineering” in such sensible areas that need the integration of engineering skill and knowledge from different fields of technologies. An analysis of the compiled human shortcomings databases (see Figure 2.1) has given a good chance to analyse the human shortcomings in the wide area of engineering activities. At the same time it is a very sensitive domain and so, for understandable reasons, the companies involved are anonymous. To

evaluate the validity of findings it is necessary to underline that the companies concerned are worldwide known strong contributors in the field of engineering.

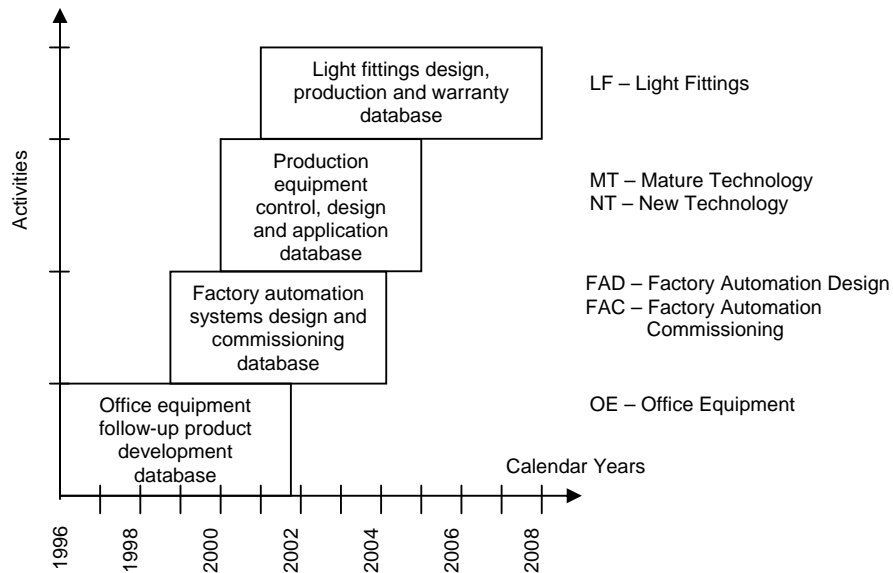


Figure 2.1 Development of human shortcomings databases

Next, statistical results of the separation of human shortcomings and technical problems at systems design and its application are presented. However, it is appropriate, at first, to specify the terms used in the further analysis. On the large scale (see Figure 2.2) all shortcomings revealed in the process of interdisciplinary systems design and application may be divided into faults **F**, mistakes **M** and technical problems **T**. Faults are wrong decisions that have no justification. Communication misunderstandings between the client and the design team or between design team members belong to the faults' category **F1**. To the category of faults **F2** belong all shortcomings connected with negligence. Mistakes have a far more complicated nature. To this category belong wrong decisions **M1**, caused by lack of core competence. Another category of mistakes **M2** is conditional and is caused by unknown matters at the moment of and they may be resolved in the course of further activities. The only real way to reduce human mistakes is to train and upgrade the personnel or to use the help of qualified experts. A special category here is technical problems **T** which involve classical reliability problems.

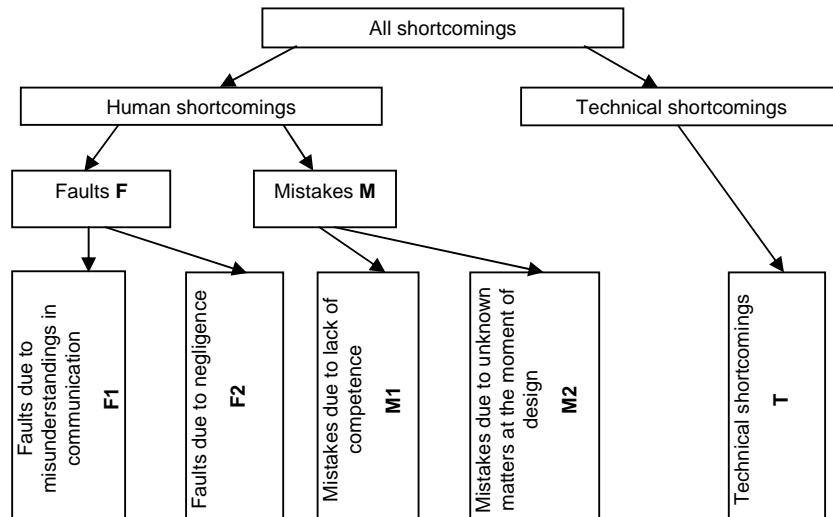


Figure 2.2 Classification of shortcomings at the design and application of artefacts

First of all, a 5-year service statistics database for non-safety-critical mechatronic office equipment was compiled where 4 generations of office machines were under observation (Tähemaa and Reedik, 2001). The database consists of up to 3,000 service actions solved in 2,000 work hours with the total turnover of 350,000 EUR. The importance of this first research is the establishment of the fact that negative synergy (asynergy) is a reality and it is caused both by incompetent decisions at design and technical problems in reliability context. The results of the failure analysis on the basis of service reasons are summarized in Figure 2.3. The analysis of the service database has proved that the negative synergy phenomenon dominates in the infant mortality period of a brand new model. For the brand new product the infant mortality period extends approximately to 1/3 of the product's commercial lifetime, for a mature product it is between 1/4...1/5. Figure 2.3a shows reasons for service actions during the first half of equipment lifetime. It is impossible to neglect the fact that at the beginning of the infant mortality period of the brand new product the share of technologies interface failures (negative synergy) from all service actions was 24%. In Figure 2.3b the course of different technologies interface failures (negative synergy) is shown.

In conclusion, Figure 2.3 presents a lot of evidence that negative synergy between different allied technologies is a reality. The obvious reason for it is the incompetence of the equipment design team and therefore interface failures are the first to be precluded by the producer in the process of follow-up product development. In this research it was impossible to differentiate between human mistakes and technical reasons and this was the object of following research activities.

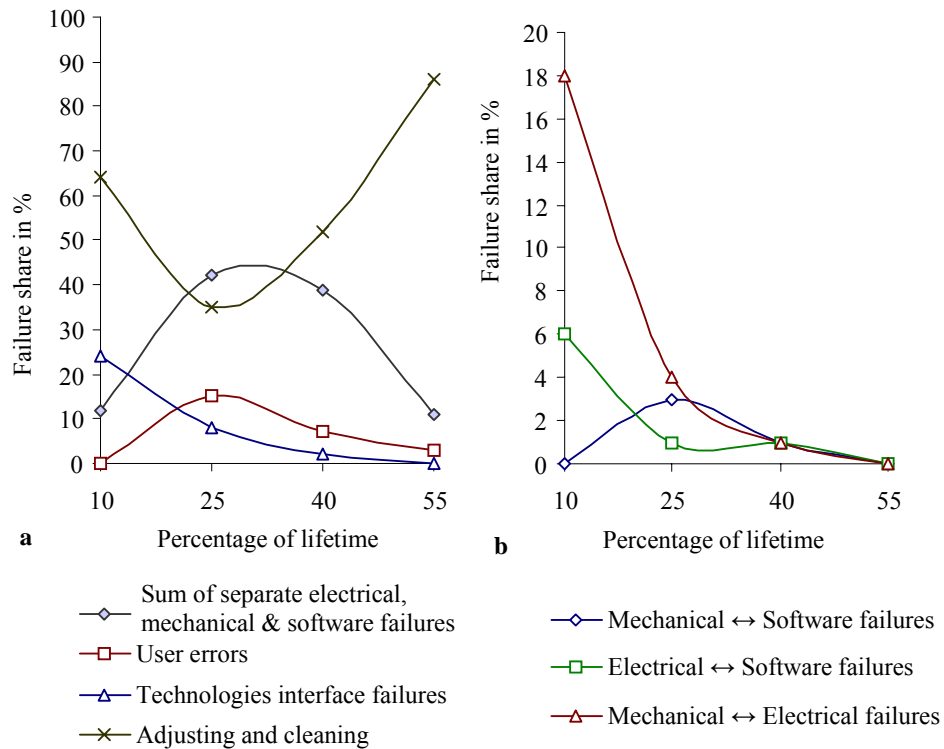


Figure 2.3 Dynamics of the share of different failures

The second database for shortcomings (see Figure 2.4) of factory automation was completed for two levels: for factory automation design (**FAD**) and for its commissioning process (**FAC**). In general, **FAD** is virtual and arranged at the system supplier's factory and it ends by Factory Acceptance Test (**FAT**). During **FAC**, the plant begins, for the first time, to produce the product that it has been built for. The basis for this database is the experience of applying 5 large factory automation systems (Kaljas et al., 2004a).

In Figure 2.4a the statistics of shortcomings for factory automation systems design and application on the Factory Acceptance Test (**FAT**) level is presented. As it is seen faults strongly dominate here. Faults from mutual misunderstandings **F1** are usually clarified during the **FAT**. In the category of **F2** comparatively simple faults dominate and all these faults can usually be easily corrected by changes in software. On the mistakes' side in the category of **M1** the incompetence of the client and the design team dominate. The share of mistakes **M2** is trivial.

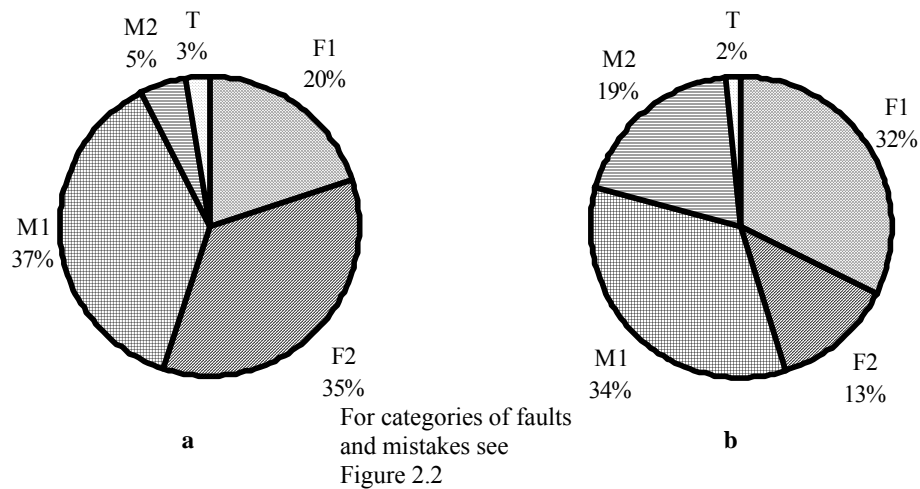


Figure 2.4 Statistics of shortcomings for the design and commissioning of factory automation systems

In Figure 2.4b the analysis of shortcomings for the factory automation commissioning stage **FAC** is presented. On the faults side the share of **F1** is still high. However, the real situation is not so gloomy as at these stages all proposals of final operators and also innovative solutions worked out during the testing are introduced. In the foreground in the category of faults **F2** there are moving faults in cabling and installation of sensors and drives. On the mistakes side in the category of **M1** incompetence in the main technological process dominates. In the category of mistakes **M2** tuning and regulation are in majority. Sometimes additional units for the smoother functioning of control systems or machines are necessary.

The third database of human shortcomings (see Figure 2.5) is completed for equipment control systems where the experience of 13,000 design and application cases is analysed (Kaljas et al, 2004b). At equipment control systems the cooperation between customers and the systems' design and application teams is so close and intertwined that only a joint analysis of shortcomings is possible. However, in this case quite an interesting difference between well-established maturity (**MT**) and comparatively new technologies (**NT**) can be observed.

In Figure 2.5a the statistics of shortcomings for equipment control systems design and application in such a well-established area as electropneumatics/hydraulics systems with programmable logic controllers on the top of hierarchy is shown. At first sight the dominating share of faults is noticeable. In the category of **F1** most of the faults are born on the grounds that 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 an apparatus with wrong parameters. A comparatively low share of technical problems can be explained by the maturity of

the components used. In Figure 2.5b the analysis of shortcomings for equipment control systems is presented where comparatively new technology, an electrical servodrives & control, is used. At the same balance of faults **F1/F2** the dominating share of technical problems **T** can be noticed that is quite natural for a new technology.

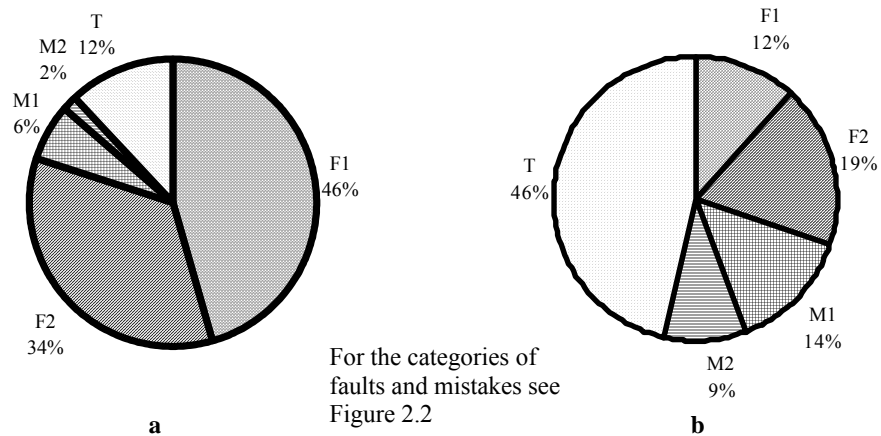


Figure 2.5 Statistics of the shortcomings analysis for the design and application of equipment control systems

Now let's have a more detailed look at the mistakes side as they are mostly common for both levels of technologies. Typical mistakes in the category of **M1** are caused by the lack of the team's core competence. To the category of mistakes **M2** it is reasonable to allocate all mistakes when it appears that it is possible to establish or to tune the exact parameters of the controlled processes only during an experimental study. The dominating share of the technical problems **T** is caused by the infant mortality of the brand new component or low quality of the mature components.

The fourth database **LF** (see Figure 2.6) was compiled for the analysis of human and technical shortcomings in the design and production of a serial product – light fittings. The scope of this database is also 5 years and more than 700 descriptions of human and technical shortcomings are analysed.

In Figure 2.6 distribution of human faults and mistakes together with technical problems in the production of light fittings is shown. The dominating share, more than 75% of all shortcomings, belongs to the technical problems' area. The main reason for technical problems is the failure of the electronic components working at a high temperature and being very sensitive to the fluctuations of the voltage. Unfortunately, during the construction of buildings electrical systems are still temporary and therefore allocated to big voltage fluctuations.

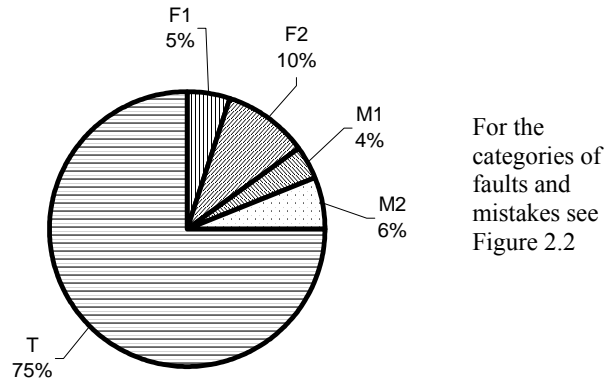


Figure 2.6 Statistics of human and technical shortcomings in the design, production and use of light fittings

On the human shortcomings side trouble is caused by too big a share of simple negligence faults **F2** caused by high self-confidence or a loss of attention and self-control at fatiguing routine production and assembly. Quite a high level of communication faults **F1** can be noticed between factory marketing and product development teams and between related factories. In the production sphere the main source of communication faults is incomplete documentation. The mistakes **M1** due to lack of competence are trivial as the factory is specialized on the production of light fittings from the beginning and the staff is experienced and stable. However, some lack of knowledge about materials and in electronics can be perceived. Mistakes **M2** are caused by lack of knowledge about the behavior of materials and electronic components at high temperature.

As one can see the scope of databases covers the main areas of engineering design activities quite completely. 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 computer systems. As the last step the service and follow-up product development phases are concerned. So it is a very valuable ground for researching the reasons for “bad” engineering and finding ways to improve the quality of engineering work.

2.2 Planning of the present research

As it was said above, the research team has a lot of experience and it has performed databases on human shortcomings concerning different quality levels of engineering activities. It enables to outline a framework for synergy-based

assurance of the quality built-in the product from its engineering side. To attain a good business it is necessary to integrate engineering design quality with other quality management activities in the company. It is important to underline that the goal of product development is not a new product but successful business with this product. In literature there was not found evidence of similar analyses of human shortcomings in quality assurance especially when the preparation for quality certification is concerned. In the present thesis we have a good chance to solve this problem as 12 years ago the author of the thesis founded a quality certification company Bureau Veritas Estonia, which has a 60% market share in Estonia. So it provides an outstanding material for the research into human shortcomings in the quality management area. This database can serve as an integrating basis of the earlier compiled databases as it reflects a full amount of human activities in the quality assurance field.

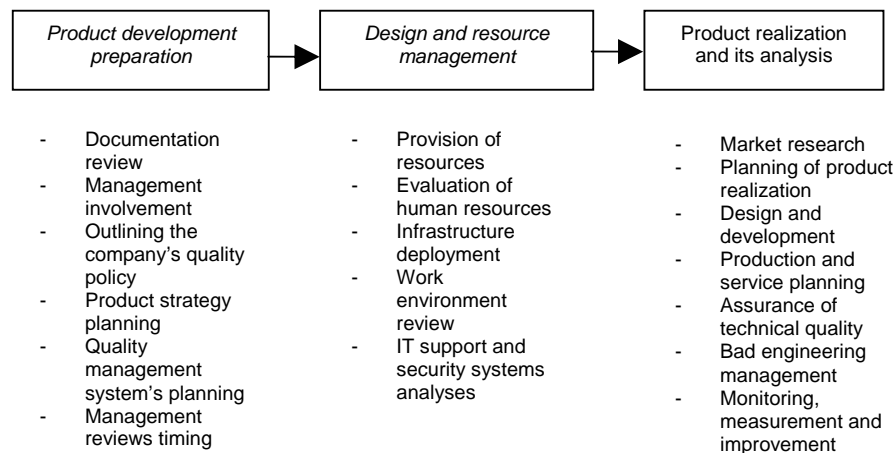


Figure 2.7 Deployment of quality management activities (ISO 9001:2000, modified)

So the present research is focused on human shortcomings in quality management activities where product development, design and resource management, product realization process and its analysis are concerned (see Figure 2.7). In the product development phase the main impact is related to documentation review. It is human nature to always fight against bureaucracy but in order to prove that the product development steps are taken correctly they should be documented and verified. In the building of an effective quality management system the involvement of management is of utmost importance because they should outline the company's quality strategy/policy and choose the quality management system. Finally, the timing of management reviews is important.

The design and resource management phase requires exact provision of resources, mainly evaluation of human resources, as it is the assets of the company that results depend on. This requires also right deployment of infrastructure which

includes the review of 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 behavior is involved in all the listed activities and the effectivity of the quality management system depends on it.

The present research is based on a 10-year database of human shortcomings where the results of more than 200 production companies' real quality certification processes were analyzed. 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 (ISO Guide No 2, 1991). 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. Auditors are qualified to perform audit according to the quality management standard ISO 9001:2000 and they mainly have two tasks. They have to check, firstly, if the documented management system covers all the necessary clauses of the standard, and, secondly, if the documented management system procedures are implemented, which means that documentation and practice should fit. In theory all companies can be certified despite the size or scope of activities. There are lots of small and medium companies certified but there also exist companies with 1-10 employees and also big companies with thousands of employees. The scope of activities varies from production to service providers. Still, the typical companies which require certification are small and medium-size subcontracting manufacturers or construction companies. The selected more than 200 production companies reflect the real market situation of certification.

The most important question here is the usability of the classification of human shortcomings used in the previous research (see Figure 2.2). As the quality management system is based mainly on human activities, it seems that after excluding technical shortcomings **T** the remaining part of the classification is fully usable here (see Figure 2.8).

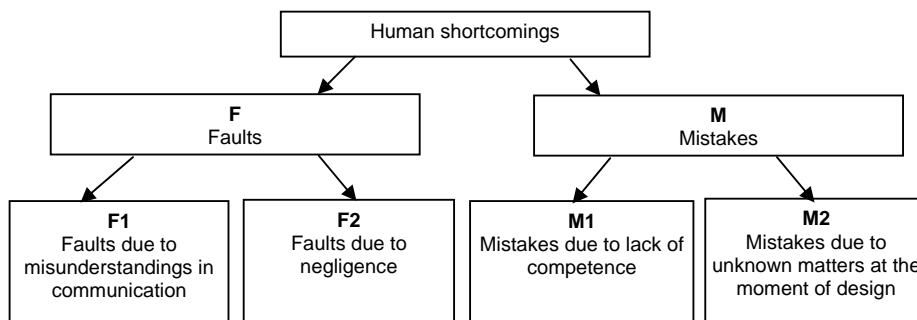


Figure 2.8 Classification of human shortcomings

The question is if human faults and mistakes are such universal criteria that they can be used at the same time for evaluating the design process and quality management system. Faults **F1** caused by communication misunderstandings really do not depend on the sphere of human activities. Neither do negligence faults **F2**. Mistakes **M1** and **M2** are connected with competence in the field of activity and are at the same universal.

Technically the research is based on scoring the human shortcomings documented in the certification process with their further classification and statistical evaluation. The database of shortcomings consists of the nonconformities and observations documented during the certification process. In reality the number (amount) of nonconformities is approximately 1-5 per company and this is small compared with the observations. The definition of nonconformities says that they should be clarified before issuing the certificate to the company. The company will have 3 months to provide evidence that nonconformity has been cleared. During the audit the auditors write down the so-called observations that are not causing a problem at the present moment but can be considered as nonconformities if the correction actions will not be taken before the regular surveillance visit. Usually the number of observations is approximately 20-30 per company. All nonconformities and observations together make an excellent basis for the analysis of human shortcomings. After collecting all shortcomings into one database in an excel file expert knowledge was used to classify them into faults and mistakes according to the definition provided in Figure 2.2. Without practical certification experience it is difficult to classify shortcomings into subgroups but it does not pose a problem for the author of the thesis as he has more than 10 years of practical auditing experience. After the classification of shortcomings the databases were analyzed and the results are presented in Chapter 2.3.

2.3 Database of the shortcomings perceived during certification

In Figure 2.9 the results of the statistical analysis of human shortcomings at the quality management area are presented. For better comparison integrated columns are used with connecting lines which have no physical content. In the further analysis only the most frequent shortcomings are listed. During the phase of product development preparation (line PDP) the typical faults **F1** are as follows: the responsibilities inside the organisation are not fully defined, the path and procedure of documentation confirmation are not clearly legitimated, absence of the overviews of clients' requirements, etc. Faults **F2** – valid instructions are not used, the introduced procedures are not followed, 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 born on grounds of lack of future perspectives when the current procedures are outdated and better solutions are available.

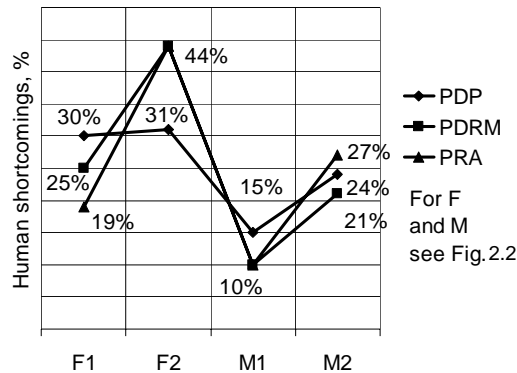


Figure 2.9 Human shortcomings in quality management

The PDRM line in Figure 2.9 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, etc. **F2** – personal development talks are not provided, professional knowledge cards are not filled in, safety regulations are not followed, warning signs are absent, etc. **M1** – misleading warning signs, incompetence in storekeeping, etc. **M2** – the existing attestation systems are not used but at the same time new ones are introduced.

The PRA line in Figure 2.9 presents an overview of human shortcomings for the realization and 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, etc. **F2** – safety regulations are not followed, internal audits are missed, suppliers’ evaluations are not provided, etc. **M1** – in the procedures there are references to non-existent requirements, conformity documentation is absent, etc. **M2** – absence of market investigations, superficiality in the planning of future strategies, absence of risk analysis, etc.

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. While having a closer look at the trends extending over the whole quality management process, it is 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 too big a share of all the shortcomings.

It is quite instructive to provide a comparative analysis of the reasons of human shortcomings in different areas of engineering activities in the quality context. In

Figure 2.10 there are compared data on human shortcomings for different levels of engineering design activities collected by the research team during the last dozen years (Kaljas et al., 2004a). The question may arise if these data are really comparable as the previous research was focussed on the quality of product design. To be more exact, the aim of the previous research was to specify the border between human shortcomings and technical (reliability) failures of the designed products and systems. Experience has shown that the two first classification levels of human shortcomings are so universal that they are fully applicable in engineering design and in quality management. However, as the gist of faults **F** and mistakes **M** is different for different fields they cannot be summarized in any way. These data can be used only in statistical form for the prognosis of the timing of processes in the field concerned. For the better comparison of the results in Figure 2.10 the failures due to technical reasons are excluded.

In the first column QA the results of the present research on human shortcomings at the certification of quality management systems are put forward. In the second column the results of human shortcomings in the design and production of a serial product – light fittings (LF) – are presented. In the third column the data on human shortcomings for the design and application of equipment control systems (EA) are shown. In the last column the data on the design and commissioning process of factory automation systems (FA) are presented.

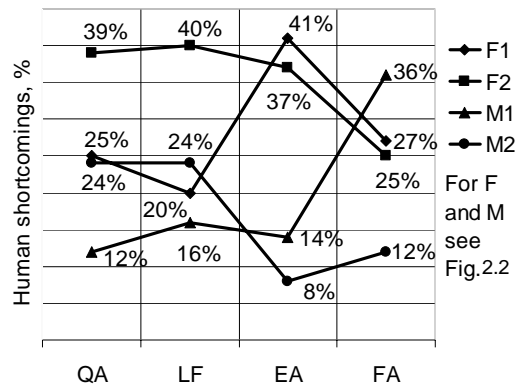


Figure 2.10 Comparative analysis of human shortcomings

As one can see the spectrum of human shortcomings in quality management is very close to real factory data (the LF case) which leads to the conviction about the universal nature of human shortcomings in a maturity company. However, in the area of equipment control the tasks always vary and work is so strenuous that the share of faults starts to dominate over the mistakes controlled by professionalism. In the more complicated area – factory automation – a lot of standard solutions are available and the share of faults is reducing but the role of mistakes **M2** is growing,

as the prognosis of the processes character may appear to be wrong for the real conditions.

Summarising the points discussed above one can see that a lot of the problems accompanying “bad” engineering are caused by human shortcomings. In the previous research efforts have been made to clear up the border between human shortcomings and technical reasons (reliability) on different complexity levels of engineering design (Kaljas et al., 2004a). A low share of technical problems is typical in systems where maturity components are used. Sometimes it is really difficult to distinguish between the failures due to reliability problems (wear, aging of the materials, etc.) and those which occurred because of wrong decisions at the choice of materials. Also, it can be difficult to detect the borderline between average negligence and negligence caused by physiological fatigue or stress due to wrong organisation of the work.

2.4 Synergy-based conception of human shortcomings

One of the goals of the present research is to initiate a framework for the effective use of the information on human shortcomings in order to increase the quality of the product design and empowering the quality management activities. As the present team has positive experience of applying the synergy-based approach to human shortcomings in engineering design (Kaljas, 2005) it is normal to apply this approach also in the field of quality management. If this attempt is successful, the way for integrating the product design quality and quality management system is paved.

Firstly though, it is necessary to define the concept of **synergy** used in the present context. The term “synergy” is derived from the Greek word *synergeia* that means collaboration. Linguistically the word synergy defines the situation where the summary effect of different factors due to their mutual compensation of weaknesses and empowering their strong sides is greater than their sum. Sometimes it is called the 2+2=5 effect (positive synergy) or 2+2=3 effect (negative synergy) and it has been successfully used in the field of business management for a long time.

The synergy treatment is based on the science field **synergetics** formulated by H. Haken in 1970s (Haken, 1983). Team members’ communication synergy has been the research area of psychologists and the synergy of a person’s inner communication that of medicine. To both areas the present research team can contribute only by analysing the registered results. Well-organised teamwork is the key to better communication synergy where capabilities of team members at co-operation are used in the best possible way by 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. The inner communication synergy of individuals determines their fitness, creativity and in summary possible contribution ability to co-operation. The increasing of the

positive synergy of human organs, neural system and psychology is the key to attaining the top form in sports, arts and creative engineering.

Let's start the synergy analysis from the personal level. A good example of synergy development is training in sports. It is obvious that to be in good shape for top achievement it is necessary that all organs, muscles and neural system have to work on the wave of full synergy. The human being is not created to be uniformly strong – everybody has weak and strong sides. During training it is necessary to develop the weak sides as much as possible or to find ways to compensate them by the development of other sides of the organism looking for ways to attain better synergy between them. Especially it can be seen at decathlon. Decathlon needs such a level of uniformity of development that in reality such a person does not exist. Success in decathlon depends on finding maximum synergy between different capabilities to support different branches of decathlon. The same applies to any creative field of human activities including engineering where progress is achieved by synergy of professional training. Without any doubt science and engineering are creative professions where discovering the new lawfulnesses and creation of novel solutions is the basis for success in professional work. Every human being is usually able to analyse his/her weak and strong sides critically. In order to achieve maximum professionalism it is not enough to acquire additional knowledge in the weak areas but in addition it is necessary to carry out selective studies to strengthen the synergy of knowledge. At the same time the ability to use the level of competence in professional work depends a lot on synergy in the functioning of all the human organism. The old saying “*Mens sana in corpore sano*” (Juvenalis) contains the main rule to reach better synergy. We all have got experience that the maximal productivity in our professional work is far from stability. When the 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 behavior and faults in communication and the negative synergy effect can easily dominate. So it is natural to conclude that human behavior depends much on its inner synergy.

Proceeding to human behavior in teamwork it is appropriate to start from the smallest and well-known team – marriage. Marriage based on real love and respect provides fertile ground for carrying out wonders. Soon the couple discovers the weak and strong sides of each other and if they find ways how to mutually compensate their weaknesses and amplify their strong sides, the ground for growing positive synergy is found. However, if they are unsuccessful in the above-described synergy-based integration, it may lead to the growth of negative synergy effects in marriage which usually results in divorce. A good example for synergy allocation is the team behavior in sporting games. In the team based on getting well with his members everybody knows the weak and strong sides of all members. So the secret of a successful game is that while playing every member must find the best strategy to realize synergy between members' capabilities.

The same is also true for engineering teams. In the present mega-competitive world the company's destiny is so strenuous and complicated and possibilities to

survive so small that for successful business maximal use must be made of the capabilities of every team member. Engineering team members are not equal in their competence and psychological capabilities. Depending on the dominating fields of their interaction capabilities team members may have roles as leaders, idea and action initiators, information searchers, evaluators, clarifiers, group norm keepers, harmonizers, trade-off organizers etc. Close attention has to be paid to the appearance of selfishness, e.g. a team member may act as a blocker, be dominant, look for recognition, keep aloof, etc. It is quite an art for the leader 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.

Returning to human shortcomings in the faults and mistakes context (see Figure 2.2) it is comparatively easy to explain them on the basis of synergy-based thinking. On the basis of the completed databases which cover human shortcomings in the wide engineering area it is possible to get initial data for their statistical evaluation and for the prognosis of activities duration. At the same time these databases are a valuable material to press down the consequences of “bad” engineering. It is most important to improve the team’s ability of synergy-based thinking. Human faults have no justification but they are a reality. However, it is normal to suppose that they are not of willful character. In teamwork faults in communication can be reduced by better synergy in communication. Still, it is difficult to apply it to communication between the engineering team and clients as these connections are usually casual and on different competence levels. Faults due to negligence are mostly a personal problem and depend on the synergy of persons’ inner communication. The mistakes side is more complicated although they can easily be explained by lack of competence. However, real competence is achieved by striving for better synergy while looking for information and new knowledge. In a normally functioning team it is difficult to expect any willful aspects of mistakes.

It is the most difficult to evaluate the role of human shortcomings in technical problems. It is quite difficult to find out if the failure was caused by the aging of the material, production quality or unsuitable integration of different technologies. In every case it is possible to find the real reason of the failure but it cannot be a basis for statistical generalizing. In conclusion, it is possible to aver that all human shortcomings as reasons for “bad” engineering can be conceived by synergy-based thinking. In addition, another important observation can be made – it is not possible to explain all quality problems only by human shortcomings as some technical problems are so far beyond human knowledge. Also, negligence can exceed physiological limits in conditions of fatigue and stress.

2.5 Conclusions of Chapter 2

1. The databases of human shortcomings completed by the research team cover a wide area of engineering activities. These databases are a reliable ground for the statistical prognosis of product development duration at the design of interdisciplinary systems. At the same time the analysis of human shortcomings is not only the key to recognizing the reasons for “bad” engineering but also a springboard for empowering the quality concept in engineering design.
2. The methodology of the research into human shortcomings in engineering design and application is also a suitable basis for research into human shortcomings in quality management systems what becomes evident in the process of quality certification.
3. The completed database of human faults and mistakes revealed in the process of quality certification is a reliable basis for the development of an effective tool for self-evaluation in the process of preparing the company’s quality assurance system for certification.
4. It is shown that all human shortcomings observed in engineering design, in product realization and at the certification of quality management systems can be treated as synergy-based. The formation of “bad” engineering is mainly due to lack of synergy in teamwork or in a person’s inner communication.

3 DEPENDENCY STRUCTURE MATRIX TECHNOLOGY AND THE SYSTEMS ENGINEERING FRAMEWORK FOR QUALITY ASSURANCE

3.1 DSM technology and its applications

The research team has a long positive experience with the DSM technology for the development of the methodology of the interdisciplinary systems design. So in the perspective of further integration the desire to use the same approach also for the analysis of quality management systems is quite comprehensible. The basis of the matrix analysis was provided already in the 19th century by A. Gayley and W. R. Hamilton. The theory of matrixes was finally formed at the end of the 19th century and at the beginning of the 20th century by K. Weierstrass and F. G. Frobenius. The Dependency Structure Matrix technology which interests us was developed by Steward (Steward, 1981a). Due to outstanding capabilities of describing the interactions of systems' components, the use of the matrix methods has become more and more popular (Erixon, 1998; Pimmler and Eppinger, 1994; Suh, 1990; Clarkson et al., 2001; Malmqvist, 2001; Morelli et al., 1995). Eppinger has used this approach for the analysis of the product architecture of large-scale engineering systems and complex interactions between product components, their design process and supporting organizations (Eppinger et al., 1994). As in the course of time the use and analysis of matrix-based approaches has broadened beyond Steward's application, nowadays the precedence and design structure matrix methods are broadly called *dependency structure matrices* (DSMs).

Dependency matrix-based methodologies are advantageous for modeling many types of systems, networks, and processes. Their 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. The DSM is used in product development, project planning, project management, systems engineering, and organization design. Interface matrixes, often called N^2 diagrams in the systems engineering field, are commonly used to display subsystem and component interactions. Similarly, network topology matrixes are used to capture the relationships in an organization (Lorsch 1972). All this gives enough evidence that the DSM technology is also a suitable tool for the synergy-based analysis of quality management systems.

A DSM is a square matrix with identical row and column labels. The matrix shows the interaction of each element with every other element, highlighting complex relationships between components, teams, or activities. The differences in DSM-based applications are given in Figure 3.1.

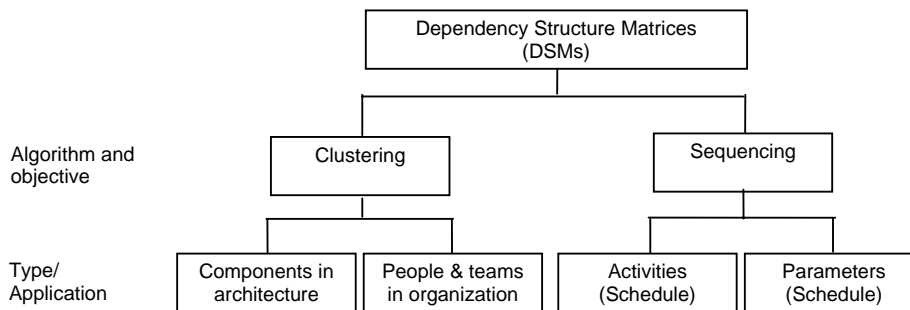


Figure 3.1 Classification of DSM Types (Browning, 1998)

A component-based DSM documents interaction between elements in complex systems architecture. This type of the DSM provides us with the principle of taxonomy which helps differentiate these interactions. After developing taxonomy for interactions, an optional quantification scheme helps weigh them relative to each other. Pimmler and Eppinger provide an example of how such a scheme might be approached (Pimmler and Eppinger, 1994). In this case off-diagonal square marks in the DSM are replaced by a number - here, an integer -2, -1, 0, 1, or 2. In the design process negative synergy seems to be excluded as the aim is to attain maximal positive synergy. 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 and Clark, 1998; Rechtin, 1991; Sanchez and Mahoney, 1997). At synergy-based design it is a valuable tool in the details' domain to empower the modularization.

A team-based DSM 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, 1998). So the first evaluation given to the team-based DSM on the field of quality management seems to make out a case for further research.

The key to building and analyzing an activity-based DSM lies in understanding the concept of iteration and the difference between serial, parallel, and coupled activities. Figure 3.2 depicts these three activity types as time-based flows with their DSM equivalents below. A subdiagonal mark in an activity-based DSM indicates information feedforward, while a superdiagonal mark exhibits information feedback. Thus, information flows in a counter-clockwise direction.

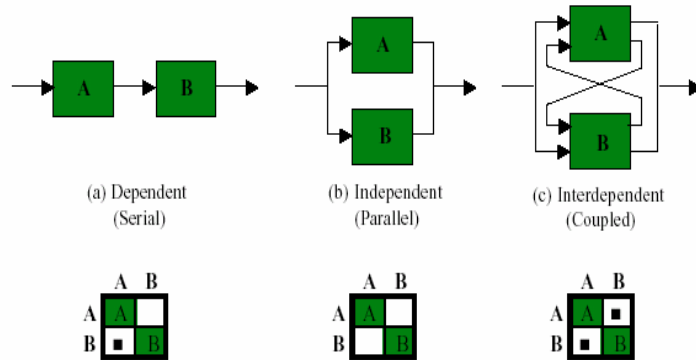


Figure 3.2 Two activity information flows and their DSM equivalents (Browning, 1998)

An iteration perspective provides a more sophisticated view of rework in the design process. The first step towards reducing the cycle time and variation of product development lies in minimizing unintentional iterations. In its nature the described process is very close to the realities of the synergy-based design process and without any doubt to the preparation process for quality certification. So this DSM application deserves a closer look.

As an example of activity-based DSM application, consider the matrix of activities and information flows in Figure 3.3. By rearranging the rows and columns, the amount of feedback is reduced – as evinced by the paucity of squares above the diagonal. This reordering is called *block diagonalizing* the matrix, and it can reveal improved activity sequences. The goal is to get the matrix in block diagonal form – i.e., lower triangular with any remaining superdiagonal entries in blocks along the diagonal. Steward (Steward, 1981b) and Warfield (Warfield, 1976) present algorithms that provide a unique block diagonal form for any DSM. Figure 3.3 shows how series and parallel activities appear in the DSM. Block diagonalizing also identifies blocks of coupled activities, such as L, J, F, and I. These larger blocks along the diagonal essentially represent the critical path of work duration. The nodes shown in Figure 3.3 represent logical places along the critical path to locate “toll gates,” opportunities for project review. This opportunity fits very well with the synergy-based design process and also synergy-based analysis of the quality management system.

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. Finally, it must be decided which activities in an iterative procedure to begin first. Steward (Steward, 1981b) provides many insights regarding this step. Rogers’ DeMAID4 software (Rogers 1989; Rogers

1996a; Rogers 1996b) uses a genetic algorithm to determine the best activity-based DSM arrangement.

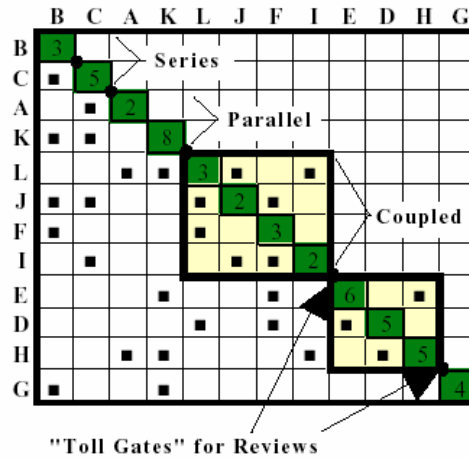


Figure 3.3 Partitioned activity- based DSM for hypothetical process shows process sequence (Browning 1998)

Here it is possible to introduce quantitative characteristics of interactions (synergy) into the quality assurance process. The synergy in brackets means that depending on the financial conditions the synergy-based optimization can be applied to a limited number of interactions. The experiences of developing the methodology of the interdisciplinary systems design have shown that it is reasonable to use three steps of integration evaluation: 0 – interaction is marginal, 1 – interaction is moderate and 2 – interaction is strong. At the design the negative values of interactions (synergy) are not allowed. In quality assurance the situation is different as the analysis is used for the existing situation in a company. In case of quality assurance probably the moderate negative synergy (-1) in communication seems to be possible, but it is impossible to run a company at negative synergy index -2.

In the parameter-based DSM application design process modeling takes place in a top-down fashion. Starting with high level activities, processes are broken down into greater detail. This is a valuable conclusion as it coincides with the essence of the vertical causality law in systems engineering (see Part 3.2). The method for building and analyzing a parameter-based DSM is similar to that used for an activity-based DSM. The analysis proceeds using a block diagonalization algorithm, followed by potential “tearing” of interfaces (choosing where to make assumptions) and/or acceptance of iteration. Another goal could be to minimize what Krishnan (Krishnan et al., 1997) has called design “quality loss,” the over-constraining of downstream options by upstream decisions. However, it may also be useful for planning quality management in a newly founded company.

Summarizing all the above-analyzed about the DSM technology it can be concluded that the four types of DSMs discussed in this chapter - component-based, team-based, activity-based, and parameter-based - have different applications and represent different types of approaches, but all of them demonstrate the chief strength of matrix-based approaches: concise, visual representation of complex relationships. This is a very useful basis of synergy-based thinking. Component and team-based DSMs are optimized via a clustering algorithm where the objective is to decompose the system into clusters along the diagonal. In contrast, activity- and parameter-based DSMs are time sequenced and are optimized by first attempting to place all interaction marks below the diagonal, thereby minimizing feedback. Remaining superdiagonal markers are grouped in blocks as close to the diagonal as possible (block diagonalization), minimizing the extent to which these unavoidable iterations impact in the process.

3.2 Search for suitable systems' engineering tools for integrating product design quality and quality management systems

In this part it is appropriate to discuss the following three problems. First, it is necessary to trace the line of reasoning of choosing the synergy-based approach as a metasytem for interdisciplinary systems design to assure that the quality is built in into the product. Secondly, it is essential to analyse the train of thought which results in choosing the Theory of Design Domains as a system engineering metatool for the interdisciplinary system design, enabling to organize the time-dependent course of the design process. Thirdly, it is necessary to find out the two above-described metaapproaches fit with quality management systems and if they can serve as a basis for the integration of product quality and quality management concepts.

In the 1970s, the world market of industrial products appeared to be full and industry arrived at the truth that in hard competition for world market shares it is possible to survive only by radical cuts in product development time. Thus, different schemes for speeding up product innovation were developed, having parallel, integrated and concurrent patterns of marketing, design, production and financing. In the 1990s when the mega-competition age started, the conflict between the growing demands for functionality and quality of products at a lower price became the everyday reality in companies. 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 situation described above has had a strong impact on the development of engineering design methodologies.

The majority of the authors of methodological publications of engineering design support the strictly formulated prescriptive product design methodologies, differing mainly in the iterations structure in the staged design process: sequential (Pahl and Beitz, 1996; Suh, 1990; Hubka and Eder, 1988), cascade (Cooper, 2001;

McConnel, 1996; Smith and Reinertsen, 1992; Ulrich and Eppinger, 2004), or spiral (Boehm and Bose, 1994; Hekmatpour and Ince, 1988; Gilb, 1988). Without any doubt these methodologies have provided basic guidelines for the design of multiple successful monotecnological products. It seems that the sequential approach is more widespread in mechanical engineering design, the cascade approach in more complicated interdisciplinary systems and the spiral approach at the design of software systems (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).

The main goal of the research in the interdisciplinary systems design of the present research team has been to propose an approach helping to attain the maximum synergy of allied technologies and through this also the maximal quality of their integration. It should be pointed out that the achievement of the maximum synergy is limited by market conditions as maximum synergy costs are usually an order higher than market prices would allow. In view of classical design strategies (sequential, cascade or spiral approaches), they usually do not include special tools for integrating different technologies. In engineering design methodologies the main shortage is that they concentrate only on structural and behavioral aspects of the designed artifacts, not taking into account human aspects and market environment. In other words, most of the classical engineering design methods are purely academic. However, the effective product development process cannot be built up without taking into account the real situation in the industry and markets. The present research team has found a way out of this situation by applying the synergy-based approach to interdisciplinary systems design (Kaljas, 2005). This approach allows to join design parameters, market conditions and human behaviour under one integrating umbrella. In this way it is possible to build quality into the product from the first steps of product development.

For the realization of the synergy-based approach the DSM technology has been the first tool as it is an effective system for the presentation of product information. However, there crops up a need for an approach which would enable to integrate different DSM matrixes into the time- and task-dependent design process. The best solution here seems to be to apply the same integrating tool to both the product quality and organizational quality concepts. A more promising way for this integration seems to be the systems theory. If you look at the design methodologies on three levels – problem-solving in general, the synthesis of technical systems and the total activity of product development, the first and the last are really more universal, not necessarily strongly related to any of allied technologies (Andreasen, 1993). If to analyze the level of synthesis of technical systems, you can be convinced that the systems theory and systems thinking seem to be the only possible basis for interdisciplinary systems design (Buur, 1990; Salminen and Verho, 1992; Ringstad, 1997; Andreasen, 1993). This general strategy applied to products' design is based on the design domains' philosophy (Andreasen, 1980) where the design process consists of the succession – process, function, organ and parts domains – with a lot of possible feedbacks. In his late publications Andreasen

has concluded to consider the two first domains together (Hansen and Andreasen, 2001). In fact, each domain should be regarded as a two-dimensional plane spanned by those two parameters, as shown in Figure 3.4. Nor should the domains be viewed as a prescription of a design procedure.

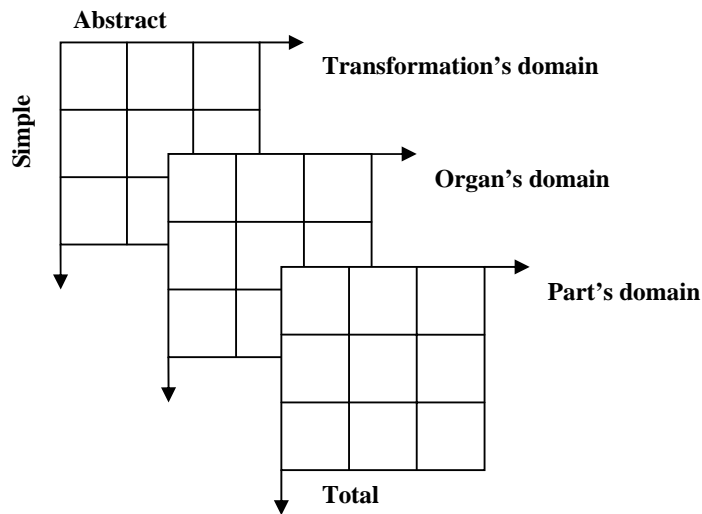


Figure 3.4 Design activities within and between three domains (Andreasen, 1993)

From the point of view of the synergy-based design of interdisciplinary systems it is possible to involve the systems' engineering approach to make it possible to control the advance in the 3-dimensional design space: not detailed-detailed, abstract-concrete and by steps of the realisation of the artefact. A suitable basis for it seems to be the Theory of Design Domains proposed by Andreasen (Andreasen, 1993). This theory is based on applying three views of the product – transformations', organs' and parts' domains encompassing substantial classes of structural definitions and behaviours of artefact (Hansen and Andreasen, 2001). This design concept is realized through horizontal and vertical causality chains. The Theory of Design Domains 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. In this context a suitable tool is the Function-Means tree as a graphical representation of the Vertical Causality Law.

After everything described above the question crops up – is the experience of synergy-based approach of product development applicable to quality management activities. For the integration of the product design quality and quality management systems it is naturally preferable to use the same toolkit. According to the research described in Chapter 2 quality management systems are based predominantly on

human relations. It does not mean that it is possible to ignore technical shortcomings. Production quality depends on the chosen production methods, the technical level of production equipment and tooling, sometimes also on temperature and vibrations in production environment, skill of workers, etc. However, all these production conditions are created by engineers and so faults and mistakes are possible here too. In Part 3.1 it was recognised that the DSM technology seems to be a suitable tool for the synergy-based analysis of a quality assurance system. The DSM technology gives an opportunity to present the relations between many optional entities in an understandable and visible way: human activities, technical parameters, different processes etc. and after transformation of matrixes to schedule them in an analysis algorithm. Also, the TDD approach can be suitable for organising the structure of DSM matrixes of the quality management system in a time- and stage-dependent manner.

When to look at the realisation of the vertical causality chain and horizontal causality chain in quality management, it is similar to engineering design. To summarise, there seems to be no objections or restrictions to use the same synergy-based framework for the design of interdisciplinary products and for the analysis of quality management systems. At the same time the integration of product design quality and quality management system concepts becomes possible.

3.3 Search for the possibilities of modeling the probabilistic duration of the quality assurance process

An important task in quality assurance is the prognosis of the time necessary for the preparation for the quality system certification. An analysis method suitable for this model of the DSM was developed in Massachusetts Institute of Technology (Cho and Eppinger, 2001; Cho, 2001). The DSM method can be used for structuring the information flows among tasks and capturing the iteration loops. This allows for computing the probability distribution of lead-time in a resource-constrained project network where iterations take place among sequential, parallel and overlapped tasks. In each simulation run, the expected durations of tasks are initially sampled using LHS (*Latin Hypercube Sampling*) method (Keefer and Verdini, 1993; Browning, 1998; Cho, 2001). After this preliminary evaluation it is appropriate to go deeper into this approach.

A special feature of the simulation model is the use of triangular probability distribution to represent the characteristic of task duration since it offers comprehensibility to a project planner (Williams, 1992a). By experience in quality certification triangular probability distribution is close to realities of quality management process. The probability density function (PDF) for this distribution is a triangle with a distribution minimum at a , a distribution maximum at c , and a most likely value at b (see Figure 3.5). The values of the parameters must be such that $a < c$, and b must be located within the inclusive region $[a, c]$, very likely $a \leq b \leq c$ (Wyss and Jorgensen, 1998). In the most common case where $a < b < c$, the

PDF can be described through probability density function $f(x)$ and cumulative distribution function $F(x)$:

$$f(x) = \frac{2(x-a)}{(c-a)(b-a)}, \text{ if } a \leq x \leq b;$$

$$f(x) = \frac{2(c-x)}{(c-a)(c-b)}, \text{ if } b \leq x \leq c;$$

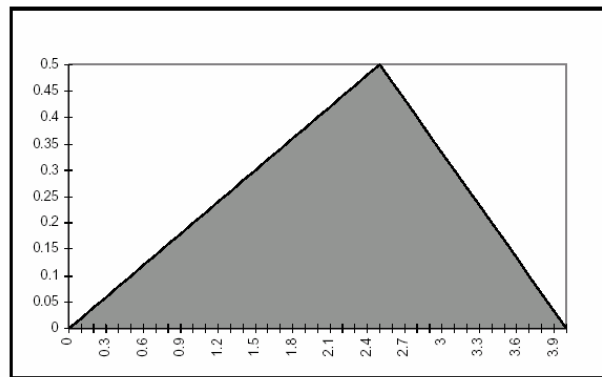
$$F(x) = \frac{(x-a)^2}{(c-a)(b-a)}, \text{ if } a \leq x \leq b;$$

$$F(x) = \frac{b-a}{c-a} \frac{(x+b-2c)(x-b)}{(c-a)(c-b)}, \text{ if } b \leq x \leq c.$$

Usually average value $E(x)$ and dispersion $V(x)$:

$$E(x) = \frac{a+b+c}{3};$$

$$V(x) = \frac{a(a-b) + b(b-c) + c(c-a)}{18}.$$



$a = 0$
 $b = 2,5$
 $c = 4$

Figure 3.5 Example of the use of triangular probability density function (Wyss and Jorgensen, 1998)

For each task, the model receives three estimated durations – optimistic, most likely and pessimistic. The expected duration is the duration between the start and end of its continuous work even though the task may iterate more than once afterwards. Remaining duration decreases over time as the model simulates the project's progress.

It has been found that assessing the 10th and 90th percentiles of the expected duration is more reliable than the extremes of the PDF which are typically outside

the realm of experience (Williams, 1992b; Keefer and Verdini, 1993). The model uses the Latin Hypercube Sampling (LHS) method (McKay et al., 1979) to incorporate the uncertainty of the expected duration of a task based on three estimated durations. 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 representing a known triangular PDF. Then, it randomly samples once from each stratum and sequences the sampled values randomly. Figure 3.6 illustrates the LHS procedure.

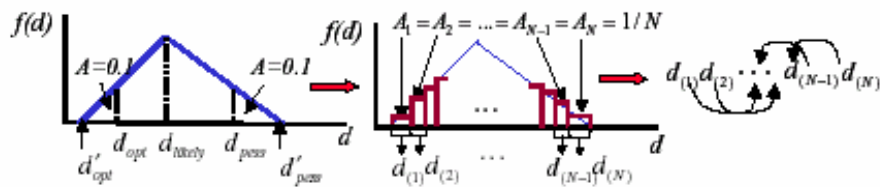


Figure 3.6 Latin Hypercube Sampling (Cho, 2001)

A very complicated problem is the formalization of interactions. In the field of quality management it is difficult to imagine the process where interactions are not necessary. Eppinger et al. (Eppinger et al., 1997) defined iteration as the repetition of tasks to improve an evolving development process. However, iteration may be referred to as rework caused by other tasks without including repetitive work within a single task (variance in duration). The model assumes that planned rework of a task is generated due to the following causes (Browning and Eppinger, 2000; Smith and Eppinger, 1997; Eppinger et al., 1997):

- 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 iteration, and the second and the third cause give rise to sequential iteration. Parallel iteration of a limited number of tasks is simulated in this model by combining overlapping and sequential iteration. Overlapping has been described as a “core technique for saving development time” (Smith and Reinertsen, 1995). The model uses the DSM representation as shown in Figure 3.7. The notation $OA(i, j)$ is used for maximum overlap amount and $OI(i, j)$ for overlap impact for $i, j = 1, \dots, n$. The former represents the planned overlap amount between tasks i and j , and it is a fraction of the expected duration of task i , d_i . This carries the assumption that the downstream task cannot be completed before the upstream task finishes. The latter represents the expected rework impact when task i is overlapped with task j by the amount $OA(i, j) \times d_i$ and it is a fraction of that amount. $OI(i, j) = 1$ implies no benefit from

overlapping. To implement overlapping strategy, it should be reasonably less than 1 considering additional risk due to the evolution of volatile preliminary information. In Figure 3.7, task *b* starts with preliminary information from task *a*. It is planned to begin earlier with preliminary information and expected to finish 20% of its work before task *a* gives a final update. However, it is also expected to rework half of the work done through overlapping to incorporate updated information from task *a*. Thus, lead time is reduced by 10% of d_2 by this overlapping.

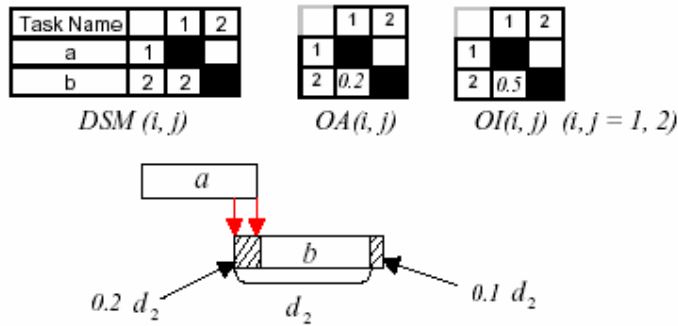


Figure 3.7 Overlap amount and impact between two tasks (Cho, 2001)

The model takes an approach similar to Browning and Eppinger (Browning and Eppinger, 2000) by explaining sequential iteration using rework probability, rework impact and the learning curve. Rework probability (see Figure 3.8) is a measure of uncertainty in sequential iteration. $RP(i, j, r)$ represents the probability that task *i* does rework affected by task *j* in *r*-th iteration for $i, j = 1, \dots, n$ and $r = 1, 2, \dots$. In the case of $i < j$, it represents the *feedback* rework caused by the change of information from downstream task *j* or by the failure of downstream task *j* to meet the established criteria. In the case of $i > j$, it represents the *feedforward* rework that downstream task *i* needs to do since upstream task *j* has generated new information after it has done its own rework. As the development processes converge to their final solutions with iterative rework, there are fewer chances that new information is generated and errors are discovered. Therefore, rework probability tends to decrease in each iteration. Rework impact is a measure of the level of dependency between tasks in sequential iteration. $RI(i, j)$ represents the percentage of task *i* to be reworked when rework is caused by task *j* for $i, j = 1, \dots, n$. Rework impact is assumed to be constant in each iteration. The learning curve measures a characteristic of a task when it repeats. $(L_{ori})_i$ for $i = 1, \dots, n$ represents the percentage of original duration when task *i* does the same work for a second time. The model assumes that the learning curve decreases by $(L_{ori})_i$ percent in each repetition until it reaches $(L_{max})_i$ which is the minimum percentage of original duration when task *i* does the same work repeatedly. Thus, rework amount is

calculated as the original duration multiplied by the rework impact and learning curve. Figure 3.8 shows the rework probability and impact for sequential iteration using the DSM representation and Figure 3.9 illustrates the learning curve.

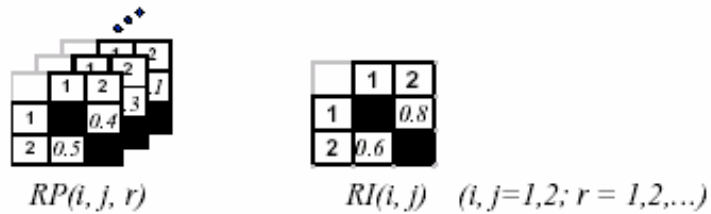


Figure 3.8 Rework Probability and Impact (Cho, 2001)

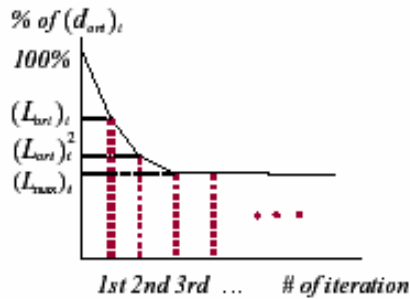


Figure 3.9 Learning Curve (Cho, 2001)

This complete treatment for the evaluation of the time for iterations, reworks and learning is nearly exhaustive for the evaluation of quality assurance activities. It is clear that in real situations a lot of simplifications can be used but these must be well founded. Anyway, without such a deep comprehension of iterations, rework and learning it is impossible to determine the initial data for starting the modeling process to simulate the whole process of probabilistic duration.

3.4 Conclusions of Chapter 3

1. The dependency structural matrix (DSM) technology is an advantageous tool for modeling at interdisciplinary systems design and quality management systems. Due to their ability to represent the complex relationships between the matrix inputs of a system in a compact, visual and analytical format they are most suitable for the application of the synergy-based approach.

2. From the point of view of the synergy-based design and quality management system analysis all the four types of the DSM: architecture-based, team-based, activity-based and parameter-based are useful for managing the complexity of the system, but their choice depends on the content of the task to be solved and the need to use clustering or sequencing algorithms.
3. As a suitable metatool for the synergy-based integration of the product design quality and quality management concepts the Theory of Design Domains (TDD) is a reasonable time- and task-dependent framework to control the advance by steps in quality management activities. By integrating the DSM technology and TDD principles it is possible to create a good quality management environment empowering the capability of a company to prepare its quality management system for certification.
4. For the probabilistic prognosis of the duration of the quality management process where iterations take place among sequential, parallel and overlapped tasks the probabilistic event simulation method is usable. In each simulation run, the expected duration of tasks can be initially sampled using the Latin Hypercube sampling method that allows to take into account the time for reworks and decreasing learning time.

4 SYNERGY-BASED APPROACH TO THE INTEGRATION OF PRODUCT QUALITY AND QUALITY MANAGEMENT SYSTEMS

4.1 Synergy-based approach to optimization in engineering

The goal of the present research is to initiate a framework for the effective use of the information on human shortcomings in order to increase the quality of the product by integrating engineering design quality and quality management concepts. It is obvious that for this a meta-approach is needed and it seems that one of the possibilities is to involve a new paradigm into quality assurance – the synergy-based approach (Tähemaa and Reedik, 2001). The synergy-based approach makes it possible to collect design parameters, market conditions and human factors under one umbrella.

The concept of “synergy” is defined in Part 2.4 of the present thesis and following is focused on synergy-based optimization. In reality while joining or integrating two details or processes, the result is always less or bigger than 2, depending on the synergy of their interaction. The classical example for this is comparing the real Eiffel’s tower built of steel and a hypothetical one made of pure concrete. If to summarize them by synergy-based integrating using the characteristics of steel and concrete in the best way as ferroconcrete (physical optimization), the sum $1+1=$ is much more than 2. Thus, there is “something” that makes integration successful and it is usually called a “positive” synergy. However, sometimes we witness an unfortunate integration of allied technologies or procedures unsuitable to accomplish the planned task. For symmetry, it is appropriate to call it a “negative” synergy. Some critics ignore the term “negative synergy” as they are used to think that synergy has always a positive meaning. Linguistically the opposite to synergy is asynergy. However, in the present context it is purposeful to stress the dynamics and direction of effects from synergy-based optimization and therefore the pair positive/negative synergy is the most appropriate.

The essence of the synergistic approach to engineering design and its application is seen in Figure 4.1. In design activities it is necessary to make a decision at any interaction on the DSM matrix field about the compensation of mutual weaknesses of the combined elements or technologies and about the amplification of their common useful and synergy-based optimisation effects. The typical examples in this field are ferroconcrete, ball-pens, mechanisms for micro-movements etc. Successful teamwork is the main source of positive synergy. On the negative synergy side the leading role belongs to human shortcomings 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.

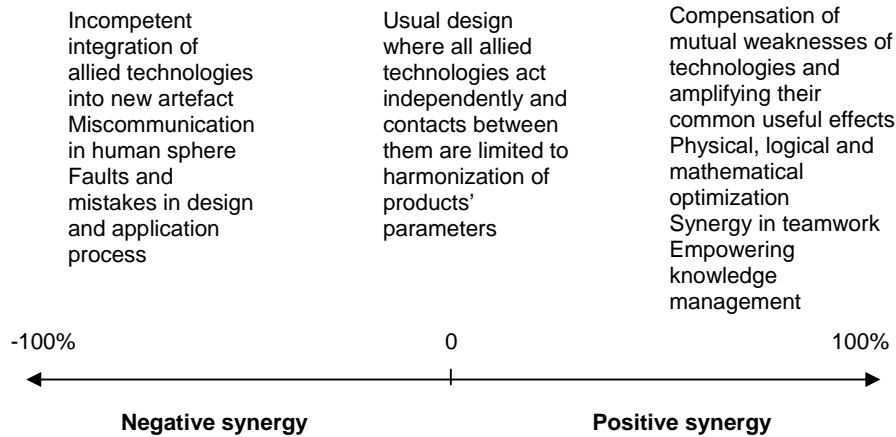


Figure 4.1 Deployment of positive and negative synergy

Generic foundation of positive synergy is optimisation in its wider interpretation. During the whole history of engineering design one can notice the striving for the optimisation of the result. The simplest way is logical optimisation. In complicated situations, beyond the grasp of human brain, we have an opportunity to apply mathematical tools. However, the success of the analytical approach depends on the perfectness of logically developed structure and the level of knowledge about the real physical processes in the product. So it is possible to assert that there are three ways of optimisation – physical, logical and analytical. In reality all these three approaches complement each other, calling forth total synergy of performance.

The precondition for granting physical synergy at the interaction of different technologies is the comprehension of the gist of integrated processes on such a level that it is fully possible to control these processes. The basis of synergy-based optimization is generalized by Haken (Haken, 1983) in his “enslaving-principle” saying that the dynamics of fast-relaxing (stable) modes is, as a rule, completely determined by the “slow” dynamics of only a few “order-parameters” (unstable modes). Earlier the order-parameter concept was used by the Ginzburg-Landau theory of phase-transitions in thermodynamics. These order-parameters can be understood as the amplitudes of the unstable modes of macroscopic patterns due to reducing the degrees of freedom through the self-organisation of nonlinear microscopic patterns. The experimentally well-founded cases of physical optimization belong to the early works of the present team. The fundamental research into the interaction of the laminar jet and an inclined scale penetrating crosswise into it resulted in the discovery of a high accuracy aerodynamic effect which led to the development of pneumatic sensors with an accuracy of $\pm 0,6 \mu\text{m}$. This result exceeded the world level achieved at that time more than 10 times. The idea of this achievement lies in the use of the balance of sticking and tearing off the two-layer jet on an inclined scale edge where the inside layer was locally

turbulized (Leschenko et al., 1972; Neve and Reedik, 1975). In this case the angle on scale and local turbulication served as order-parameters. The power of synergy-based optimisation has given some other outstanding results the most important from which is probably the design of relay servo-drive stopping 500 kg mass on classical lubricated slides with repeatability $\pm 1 \mu\text{m}$ (Leschenko et al., 1972). This was an outstanding achievement for pneumo-hydraulic drives in these days (1970-1971). The idea of the achievement was based on the use of relay switching and the optimisation of the control canal in order to work close to the sound velocity, both serving as order-parameters. It seems that it was probably the first use of divided intelligence which became so popular in 1990s. In 1975-76 the synergy-based approach was used in City University of London to reduce the diameter of the classical flow visuation paraffin steam jet about five times (Neve and Reedik, 1975). The idea was to form the jet by a “wet” nozzle where the nozzle eye was controlled by nozzle temperature. Later the synergy-based optimisation philosophy was used around 1980 to increase the accuracy of backpressure pneumatic sensors 2...3 times (Reedik, 1985). The idea of this invention was the creation of resonance as an order-parameter in the recirculation zone of the backpressure sensor. Around 1990 a successful research was carried out into pneumatic jet massage devices where the synergy-based approach was allocated to customize the massage pressure and cooling effects (Martin et al., 2000). Since 1996 efforts have been made to apply synergy-based thinking to the design of interdisciplinary systems.

One of the requirements for moving ahead in synergy-based engineering design methodologies is the quantitative evaluation of synergy. Quantifying the synergy in artefacts proposes the existence of a universal scale to measure the products' performance. The scale of measuring may start from 0 for a conditional interdisciplinary synergy-free product. So far for the evaluation of the positive synergy it is possible to use only a relative parametrical scale based on benchmarking the similar products on the market. The maximum value on the positive side of this scale means reaching the maximum synergy (100%) where everything has been squeezed out of physical processes. It is impossible to say where the real maximum is, as it means the fixation of the end of any development and further research. The validity of such an approach has the same value as repeated unsuccessful predictions of human limits in sport. However, in the field of engineering close to 100% limit is reached in space and nuclear technology equipment.

Anyway, it is not possible to ignore quantitative characteristics of negative synergy facts. Negative synergy is closely related to the reliability characteristics of the system and it reveals itself mostly in the infant mortality period of a new product and its wear-out stage of the life cycle (Tähemaa and Reedik, 2001). The classical understanding of a system's reliability is not very suitable for interdisciplinary systems as besides mono-technology failures there are also combined failures or effects of incompatibility on the allied technologies interfaces. A particular component may fail as a direct result of a physical reason,

or it may fail as a result of a chain failure of another component of the system. The chain failure can be treated as the negative synergy between allied technologies. In the synergy context reliability can be treated as a process where the synergy of the operation of components is gradually reducing (wear, emission, etc) and stops functioning when accumulating negative synergy reaches its extreme value 100%. Negative synergy effects reveal themselves most strongly at the beginning of the infant mortality period of a brand new product and due to the gradual upgrading of the product these effects are decreasing and the infant mortality period is nearing to the mature one.

It is obvious that to attain the maximum synergy of interdisciplinary systems it is necessary to take into account all substantial interfaces between the components and modules of the system carrying the features of different technologies. Using the DSM technology matrixes sequenced by design tasks, parameters or processes synergy-based optimization is introduced by applying it to a part of selected and weighed interactions. Applying the synergy-based approach to all interactions is the norm at the development of the products for space, nuclear or military needs. For usual consumer products it is necessary to set up constraints to limit excessive development time and cost. One of the constraints is the statistical know-how that normal consumer products are about an order cheaper than top-quality space and nuclear technology ones. The simplest way is to determine the price level by the market analysis. There are also available statistical data about the cost of product development for different complexity of production.

In summary we have enough possibilities for the preliminary delimitation of the synergy and quality level of the product. The main problem here is to obtain the ability of synergy-based thinking. In reality it means the effective use of synergy-based optimisation based on the integration of logical, mathematical and physical ways of optimisation. Sometimes physical optimisation needs expensive experimental research. Mathematical optimisation has value only on condition that the mathematical model describes the interaction process sufficiently exactly. Despite everything, the real key to better synergy is the compensation of mutual weaknesses and the amplification of common useful effects in interactions. The success depends on the core competence of the team. Excluding wilfully caused negative synergy, the main reason for it is always the insufficient competence of the design team.

4.2 Assurance of product quality through synergy-based design

The most important recommendation for the use of a novel design methodology is its testing. So far the proposed synergy-based design methodology has been tested for the first two matrixes (Kaljas and Reedik, 2005). The testing object was the high accuracy pneumatic positioning device. The primary expert information for completing matrixes was based on wide questioning of Estonian and Finnish specialists in the field of automation. As a result of the synergy-based design of the

positioning device the main principles of it were tested experimentally and the accuracy of the positioning device and its competitive price level was proved. However, before the integration of product quality and management quality schemes it is obviously necessary to test the synergy-based design methodology to its full extent in the real industrial environment when real design parameters, market conditions and human shortcomings are taken into account. It also gives a firm basis for further synergy-based treatment of the managerial side of quality. In the framework of the present research the complete testing of the entire synergy-based design methodology on the basis of the light fittings design was provided. Despite seeming simplicity modern light fittings are a clever integration of mechanical support structure with optics, thermal engineering and electronics.

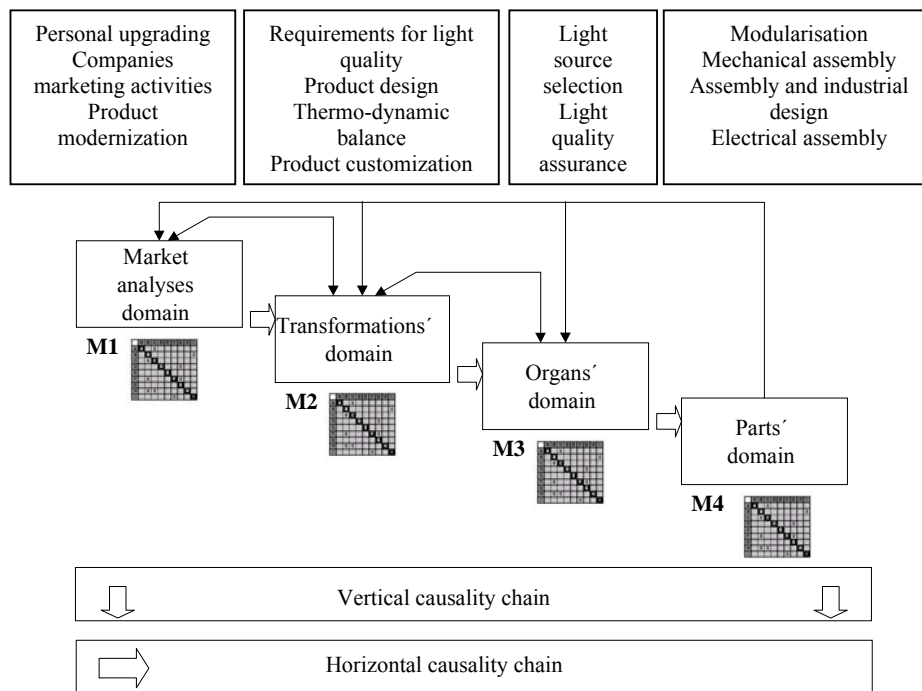


Figure 4.2 The integrated model for light fittings system design (modified from Kaljas and Reedik, 2005)

Further the integrated model of synergy-based design was modified for light fittings (see Figure 4.2). In the upper part of the illustration the specific content of design domain matrixes is opened. For the matrix for the market analysis domain the DSM for 16 inputs was compiled, characterizing trends in the present market environment, the product strategy of the company and its personnel's competence in product development (see Figure 4.3). 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 conditions of the decreasing or increasing market. There is no need to arrange inputs in order as it is sequenced by mathematical treatment of the matrix. All inputs must only be preliminarily numbered to give a possibility to involve the synergy relations between inputs of the matrix and therefore the numbers of inputs must be the same on vertical and horizontal axes. The number of inputs is practically not limited and depends only on the complexity of the product. The interactions strength is characterised on a 3-step scale: 0 - indifferent (left blank), 1- interaction is moderate and 2 - interaction is strong. Very important here is the direction of interaction and in case of use of results of previously completed task in the following one only the first should be written into the matrix.

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

Figure 4.3 The market relations' DSM before sequencing

In Figure 4.4 the previous matrix has been allocated to sequencing transformation. In this transformation process activities are ranged with the goal to move all interactions 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 possible. 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. However, it is necessary to remember the main goal of the present research – 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 it is necessary to provide an analysis of the design team's competence on the first level 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.

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

Figure 4.4 The activity-based market analysis DSM after sequencing

In Figure 4.5 the parameter-based transformations' domain DSM after sequencing is presented. 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 this level's activities 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 output parameters where variations of the principles of montage and additional functions or protection are estimated.

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

Figure 4.5 The parameter based transformations' DSM after sequencing

In Figure 4.6 the organs' domain DSM is presented. The focus of this matrix is to choose the most suitable physical effects for the realization of these functions selected at the analysis of the previous matrix. On the first level all assembly problems are gathered including the way of montage with allocation to the producing, assembly and service quality of the parts. On the second level the 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 systems. As one can see the solution of the described problems paves the way to the detailed design and assembly drawings.

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

Figure 4.6 The organs' domain DSM after sequencing

In Figure 4.7 the last DSM – the details' domain one is presented. It is reasonable to allocate this matrix to the structuring as it also serves the interests of product modularisation. 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	17	18	19	20	21
Holding	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Holder for components (on socket side)	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Holder for choker	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Clamp for once-through wiring	1	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Tightening silicone	1	5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Fastening with screws	1	6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Fastening with welding	1	7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Reflector	1	8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Reflector fixing frame	1	9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Glass cover	1	10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Glass fastening (hinges and screws)	1	11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Choker	2	12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Socket	2	13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Starter	2	14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Condenser	2	15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Wiring	2	16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Terminal board	2	17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Lamp	2	18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Feedthrough	2	19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Glass seal	2	20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Temperature proof wiring with protective cover	3	21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	

Figure 4.7 The details' domain DSM after structuring

It is also necessary to pay attention to the fact that process sequencing is only the first step of the design process. However, a trustworthy roadmap for the design process has been created enabling to keep 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. Further the design process is concentrated on the synergy-based approach to interactions in the matrix setting priorities for them to keep product development costs in market-driven limits (see Part 4.1 of the present thesis). To every block forming as a result of mathematical sequencing it is possible to apply the probabilistic prognosis of optimistic, most likely or pessimistic duration. Only the initial framework of the design process of light fittings is described without plunging into details. However, there is enough evidence that the synergy-based methodology is a suitable tool for the integration of different technologies.

4.3 Framework for synergy-based quality management system

The success in the synergy-based design of interdisciplinary systems has had an impact on the research into the possibilities to use the philosophy of synergy-based thinking also in the quality management area and to use it for the integration with the product design quality concept into one unified system. As one can see that the quality management system is mostly based on human shortcomings, it is appropriate to go deeper into human activities in the quality management context. For this a 10-year database of human shortcomings was compiled where the results of more than 200 production companies' real quality management systems certification processes are analysed (see Part 2.3 of the present thesis). The results of this analysis may be used for the statistical probability evaluation of the time for iterations, reworks and learning at the preparation of the company for quality certification.

In any design and quality management process the main driving factors are the engineers and people from the business and administration side with their experience, inherent faults-mistakes and competence. So, there is an obvious need to help them to find a more optimal way of using their capabilities and avoiding human shortcomings. A good basis for this development seems to be the synergy-based approach to quality management.

By integrating (see Figure 4.8) the technology of Dependency Structure Matrixes (Steward, 1981a; Eppinger, 1997) and the Theory of Design Domains (Hansen and Andreasen, 2001) it is possible to involve time and competence dimensions also in the quality management area (see Part 3.2 of the present thesis). The proposed model makes it possible to take into account both "soft" parameters of integration – market conditions and human aspects. In reality it is necessary to compose 3 different matrixes (see Figure 4.8) for different quality management activities groups. Matrix 1 presents the activity type DSM that allows to take into

account marketing trends and to initiate synergy-based activities in product strategy and its quality management planning so 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 the 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.

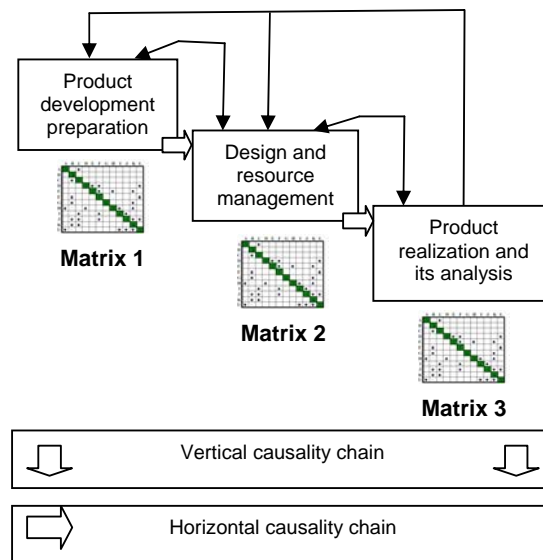


Figure 4.8 The integrated model of quality management

For the product development preparation domain the DSM for 14 inputs was compiled, characterizing trends not only in document control and review activities but also in companies' strategy and policy statements and management competence in product development preparation. Here is necessary to notice that some rules of completing the matrixes presented in Part of 4.2 are for clarity and unity reasons repeated. There is no need to arrange inputs in order as it is sequenced by 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 vertical and horizontal axes.

The synergy dimension is introduced into the further analysis of matrixes by the synergy-based approach to the selected interactions in the matrix to confine the resources amount determined by the quality level. The integration dimension is introduced to the DSM in the form of the evaluation of inputs interactions power of parameters and processes on a 4-step scale. For quality management activities the

next scale is suitable: 2 - interaction is strong, 1 - interaction is moderate, 0 - interaction is practically absent, -1 interaction is negative on a moderate level. This may happen when the interest of different company departments collides. It is an abnormal situation and during the matrix analysis it is the first priority to find a positive solution.

In Figure 4.9 the activity-based matrix for product development preparation, already allocated to sequencing transformation, is shown. In this transformation process activities are ranged with the goal to move all interactions 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. 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	1	2												1
Control of documents	1	2	1	1	2												2
Control of records	1	3	2	2													3
Management involvement	2	4	1					2	2	1							4
Customer focus	2	5						1	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	2	1					7
Quality objectives	2	8	1					2	2	2	1						8
Quality management system's planning	2	9		1	1			1	1	1	1						9
Responsibility and authority	3	10		1	1								2	2	2	1	10
Management representative	3	11		1	1								2	2	2	1	11
Internal communication	3	12	1		1								2	2	2	1	12
Management reviews input and output	3	13	1	1									2	2	2	1	13
Management reviews timing	3	14	1	1									2	2	2	1	14
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	

Figure 4.9 Product development preparation matrix

Now we have reached the first goal – all activities are sequenced and grouped on the levels, marking the decision-making steps. The two 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 how all problems with 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 conditions of the decreasing or increasing market.

In Figure 4.10 the design and resource management DSM after sequencing is presented. 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 from 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	3	4	5	6			Block1				1
Evaluation of human resources	1	2	3	4	5	6	1							2
Competence, awareness and training	1	3	4	5	6	7	8							3
Infrastructure deployment	1	4	5	6	7	8	9							4
Work environment review	1	5	6	7	8	9	10			Block2				5
IT support and security systems analyses	1	6	7	8	9	10	11							6
Design and development planning	2	7	8	9	10	11	12	13	14	15	16	17	18	19
Design and development input	2	8	9	10	11	12	13	14	15	16	17	18	19	20
Design and development output	2	9	10	11	12	13	14	15	16	17	18	19	20	21
Design and development review	2	10	11	12	13	14	15	16	17	18	19	20	21	22
Design and development verification	2	11	12	13	14	15	16	17	18	19	20	21	22	23
Design and development validation	2	12	13	14	15	16	17	18	19	20	21	22	23	24
Control of design and development changes	2	13	14	15	16	17	18	19	20	21	22	23	24	25

Figure 4.10 Design and resource management matrix

In Figure 4.11 the product realization and its analysis DSM is presented. The focus of this matrix is on choosing the most suitable way for the realization of these functions selected at the analysis of the previous matrix. On the first level all market and customer related activities are gathered. On the second level the main attention is on production and service planning. The third level is fully focused on 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	2	3	4	5	6			Block1														
Planning of product realization	1	2	3	4	5	6	7																	
Customer-related processes	1	3	4	5	6	7	8																	
Determination of requirements related to the product	1	4	5	6	7	8	9																	
Review of product requirements	1	5	6	7	8	9	10																	
Customer communication	1	6	7	8	9	10	11																	
Purchasing	2	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Production and service preparation	2	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Control of production and service provision	2	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Validation of processes for production and service provision	2	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Identification and traceability	2	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
Customer property	2	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Preservation of the product	2	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Control of monitoring and measuring	3	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Customer focus	3	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
Internal audit	3	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Control of nonconforming	3	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Analysis of data	3	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Corrective actions	3	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Preventive actions	3	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Assurance of technical quality	3	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
"Bad" engineering management	3	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44

Figure 4.11 Product realization and its analysis matrix

The important part of the described synergy-based approach to quality management is the prognosis of the time for the preparation for quality certification. Depending on the preparedness of the quality assurance team to handle the matrix analysis and mathematical statistics there are 3 possible levels to use the proposed methodology. On the first level it is possible to fill in the DSM with interactions and to sequence the tasks table by hand. Already here it is fully possible to exploit the fruits of

synergy-based thinking, i.e. to use the integrated synergy-based optimisation technology for the compensation of the mutual weaknesses of quality management activities and for the amplification of their common useful effects to increase positive synergy. On the second level the mathematical matrix analysis helps automatically to sequence the activities in the matrix.

A full exploitation of the possibilities of the proposed approach (3rd level) requires an additional experience in probability evaluation and discrete event modelling. By using the appropriate mathematical tools (Cho and Eppinger, 2001) it is possible to schedule the dispersed activities by levels grouping them into submatrixes of coupled tasks (see part 3.3 of present thesis). Further 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. In Figure 4.12 the result of the probability analysis of preparation time for the activity-based product development preparation matrix block 2 (see Figure 4.9) is shown.

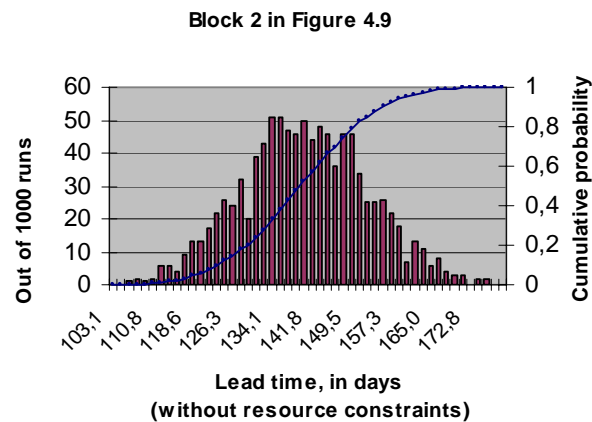


Figure 4.12 Prognosis of the preparation time for certification

It is highly qualified and time-consuming to compose a useful and suitable DSM matrix and this may be a great challenge to the quality management team. Thus, simultaneous professional knowledge of product architecture, the product development and quality management process is required. The question raises concerning the competence level required to use the proposed simulation method, although all of these mathematical tools are available in most mathematical software. A full exploitation of the possibilities of the proposed approach needs an experienced professional team. No methodology is so adequate that it can suit any competence level of the team. The low competence of the team results in an imperfect DSM where some important interactions may be absent or incorrectly evaluated. It is necessary to underline the flexibility and suitability of the described

approach for setting synergy-based priorities. It makes it possible to realize negative synergy filtration principles and to reach the optimal synergy level, set by the market, in minimal time. In conclusion, it is necessary to say that the main key to reducing negative synergy effects is to increase the synergy of teamwork and the team's overall core competence.

4.4 Integration of product quality and quality management systems into an overall quality assurance system of a company

The headline of this part once more underlines the aim of the present thesis research – to develop a synergy-based framework for the quality management system integrating it with the product design quality concept into an overall effective quality assurance system. It is not superfluous to underline once more that the two mentioned systems are so far somewhat disunited (see Part 1.4). The aim of product design quality concept is to choose a methodology that enables to build in quality in the product from the first steps of its development. The outcome of this effort is product price and performance that are competitive on the market. The quality management system has to assure the product quality in the wider framework: quality of used production equipment and tooling, qualification of producing personnel, effectivity of the quality management system etc. As the mentioned concepts are also mainly chosen and applied by the engineering team then the faults and mistakes made here can be partly treated also as human shortcomings. As the thesis mostly concentrates on human shortcomings, it may lead to a misleading conclusion that quality assurance depends totally on human competence and responsibility. In reality it is necessary to take care of all technical problems of quality belonging to classical reliability areas as it was done in earlier doctoral researches of the present team (Tähemaa, 2002; Kaljas, 2005). However, the main focus of the present research is the problematics of fighting against “bad” engineering based on the statistical analysis of human shortcomings.

The main problem here is that all are based on the human faults and mistakes statistic database which addresses the companies' situation from the past. In fact, it is necessary to develop a basic framework how to avoid human faults and mistakes in future. Thus, the integration of product quality and quality management concepts is the most crucial task of the present research. For any systems integration it is necessary to find a suitable metatool able to describe all specific features of both systems in a common language. In Parts 2.4 and 4.1 the conclusion has been reached that a suitable metatool for integration may be found in the synergy-based approach. The synergy-based approach opens a possibility to integrate market conditions, design activities and quality management activities, which are all based on human behaviour, under one umbrella. However, in order to apply the synergy-based approach to systems integration two more meta-tools are necessary: the first one for presenting and operating the system's parameters and actions information, and the second one for time- and stage-sequencing of activities. In Parts 3.1 and 3.3

the conclusion was reached that the DSM technology and TDD as systems engineering tools are those suitable meta-tools supporting the realization of the synergy-based approach. DSM matrixes enable to analyse interactions between different tasks at the different stages of quality assurance. The TDD gives the system engineering time- and stage-dependent framework to all activities. The synergy dimension is introduced to the DSM in the form of evaluating its integration power in parameters and processes on a 3 or 4-step scale. By the transformation of the DSM matrixes it is possible to solve product architecture problems and also clear up the scheduling of processes. In summary it can be said 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 and to synthesize their own roadmap algorithm to move ahead on the way of quality assurance. In this process the statistical probability evaluation of the time for iterations, reworks and learning may be used.

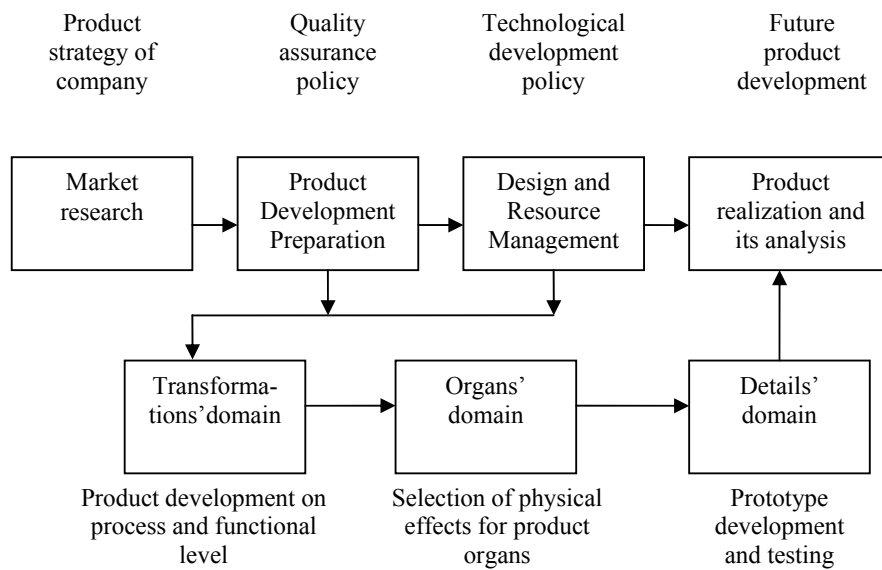


Figure 4.13 Integrated synergy-based scheme of total quality assurance

The integrated synergy-based scheme of quality assurance formed by the integration of the TDD and DSM technology is shown in Figure 4.13. The initial matrix is the market research one that allows to benchmark the company's and its product position on the market and to find out the possibilities to change the position. The quality assurance policy needs to be identified 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. The real integration of product design quality into the overall quality assurance system is coming through matrix - based analyse of transformations', organs' and details' domains. On those domains the product will be developed and through product physical realisation the prototype will be designed and tested.

However, while using the proposed tool it is necessary to be aware that the composing of a useful and suitable DSM matrix is a complicated process and may be a great challenge to the design and quality management team. The problem is that the DSM is set up on the basis of the expert knowledge and competence of the team. So the professionalism is simultaneously needed in product development and quality management processes and the success of using the proposed model depends on the existence of these qualifications. The professional team always gets help in the automatic synthesis of the optimal design algorithm that leads to a product with better performance during the shortest design time. A badly synthesized algorithm makes it necessary for the team to restructure the matrix. The described circumstances cannot reduce the values of the present approach as no methodology would be effective if used by an incompetent team.

The present practice of preparing companies for the certification of quality assurance systems according to the ISO 9001 standard is mostly based on the knowledge of the consultants helping companies during the implementation stage. The consultants know the requirements of the standards but very often they do not understand the companies' organizational problems. The proposed synergy-based methodology can help to increase the readiness level of the company for certification. The main shortage of the present certification process is that auditors who perform the certification process and companies preparing for certification are mostly concentrated on requirements written in the quality management standard ISO 9001. In reality the success of the companies' quality management system also depends on many other factors like market conditions, customer requirements, legal issues between companies, product quality etc. 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 for guaranteeing that after implementing the synergy-based approach the companies will be able to meet the requirements of certification bodies.

The practical approach to implementing the proposed method should start with forming the team of people and upgrading them to be capable of synergy-based thinking. After brainstorming it is necessary to identify the main tasks that affect the quality of the product and the quality of the management system in synergy context. After this it is possible to form a basis for finding empowering interactions between different tasks. Analyzing DSM matrixes makes it possible to get a real roadmap for the company for implementing the necessary tasks for successful certification.

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. The testing is possible only by applying the proposed approach to the results of the provided certification process. In such a

way it is possible to construct a hypothetical example certification process with minimum nonconformities and observations.

4.5 Conclusions of Chapter 4

1. The synergy-based optimization is a suitable metatool for empowering both engineering design quality and quality management concepts. The most difficult here is to obtain the ability of synergy-based thinking and use the synergy-based optimisation technology for the compensation of mutual weaknesses of allied processes and for the amplification of their common useful effects in order to increase positive synergy.

2. The testing of the synergy-based design methodology of interdisciplinary systems on the basis of light fittings in real industrial conditions showed that it is an efficacious tool for developing competitive products. The synergy-based approach to design opens a possibility to build quality into the product starting from the first phases of design and therefore it is a suitable component for building an integrated quality assurance system.

3. The synergy-based approach to quality assurance seems to be a new valuable contribution in this field. It is proved that all substantial parameters in the quality assurance process, including quality, reliability, human aspects and competitiveness, can be expressed in the synergy-based manner. It is shown that the integration of the structure matrix technology and the theory of design domains forms a most suitable basis for the synergy-based quality management system.

4. 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 personnel of the company. In such a way a suitable basis is developed to speed up the integration of the still somewhat disunited product quality and quality management concepts into an overall effective quality assurance system. The effectivity of synergy-based quality assurance system is verified by conducting a follow-up test on basis of the certification results.

CONCLUSIONS

It is appropriate to discuss the findings of the present thesis in three aspects: research results and their application, novel findings, and further development of the research. During this doctoral research the following conclusions have been reached:

1. The experience of the research team in the design of interdisciplinary systems has pointed out that a suitable integrating meta-tool for engineering design quality and quality management system is in the synergy based approach. It is shown that all substantial parameters in the quality assurance process, including product performance, reliability, human aspects, market conditions, etc. can be expressed in the synergy-based manner.
2. The database of human faults and mistakes revealed in the process of quality certification is used as a reliable basis for the development of an effective tool for the self-evaluation of the company while preparing its quality management system for certification. The effectivity of this methodology has been verified by conducting a follow-up test of the certification results.
3. Empirical studies have shown that most of human faults and mistakes noticed in engineering design and quality management can be treated as synergy-based. The formation of “bad” engineering is mainly due to the lack of synergy in teamwork or in a person’s inner communication or due to the inadequate competence of the team.
4. The dependency matrix-based (DSM) technology is an advantageous tool for modeling interdisciplinary systems design and quality management systems. Due to its ability to represent the complex relationships between the matrix inputs of a system in a compact, visual and analytical format it is a most suitable environment for applying the synergy-based approach. The DSM technology enables to make a probabilistic prognosis of the time needed for product design and quality management activities.
5. Another suitable meta-tool for the synergy-based approach to the quality management system is the theory of design domains (TDD) which is based on the systems’ engineering approach and forms a reasonable time- and task-dependent framework for controlling the advances in the quality management process.
6. The testing of the synergy-based design methodology of interdisciplinary systems on the basis of light fittings in real industrial conditions has demonstrated that it is an efficacious tool for developing competitive products. The synergy-based approach to design opens a possibility to build quality into the product starting from the first phases of design and therefore it is a suitable component for building up an integrated quality assurance system.
7. By integrating the DSM technology and TDD principles a good integration environment for product quality and quality management concepts is created. In this environment the adaptive tools are developed based on the level of competence and expert knowledge in the company in order to synthesize their own roadmap

algorithm for moving ahead on the way of the synergy-based quality assurance process. The precondition here is obtaining the ability of applying the synergy-based optimization to compensate the mutual weaknesses of allied processes and to amplify their common useful effects in order to increase positive synergy.

The novelty of the present research lies in the following:

1. The most important novelty of the present research is the synergy-based approach to quality assurance. The present thesis presents unique data about human shortcomings found in certification processes of production companies. For the first time, it has been shown that most human shortcomings in quality assurance can be treated as synergy-based.
2. On the basis of the database of human faults and mistakes in the process of quality certification a novel tool for the self-evaluation process has been developed which helps companies prepare for the certification of their quality management system.
3. It is shown that the integration of the DSM technology and the TDD is a good basis for a synergy-based quality assurance environment. In this environment a new family of quality assurance tools has been developed where the synthesis of a decision-making algorithm is based on the competence and expert knowledge of the team.

The results of the present doctoral research have been continuously tested on international scientific forums. The acceptance of the majority of conference papers for oral presentation in the conditions of strong competition has given evidence that the results of this research are original and are of wide interest.

To evaluate the impact of this research on the future ones it is necessary to point out two main tasks. The border line between technical and human reasons in “bad” engineering has been studied in sufficient detail but the rest of the quality assurance environment needs additional studies. Also, the border between human shortcomings in normal conditions and those revealed due to excessive physiological fatigue and stress is still hazy. As this is a very complicated area, specialists in both work science and medicine should be involved in the further research. Secondly, there are not enough satisfactory criteria yet for the selection of the interactions in dependency matrixes which require synergy-based optimization and up to now it is possible to rely mostly on intuition.

KOKKUVÕTE

Kvaliteeditagamise sünergiapõhine käsitlus

Doktoritöö eesmärgiks oli luua sünergiapõhine raamistik integreerimaks projekteerimise kvaliteedi ja kvaliteedijuhtimise ühtsesse kvaliteeditagamise süsteemi. Uurimuse ajendiks oli vahendite otsing, võitlemaks nii kehva inseneritöö kui ka ebapiisava kvaliteedijuhtimise ilmingutega.

Et sellele eesmärgile jõuda, tuli doktoritöös tööülesannetena lahendada 5 olulist probleemi:

- 1) läbi viia seniste kvaliteedijuhtimissüsteemide süvaanalüüs, eristamiseks neist sobivad, mida oleks võimalik integreerida toote kvaliteedi kontseptsiooniga;
- 2) korraldada kvaliteedijuhtimissüsteemide sertifitseerimise andmebaasidel põhinev inimlike vigade ja eksimuste mõju empiiriline uuring ja luua vastav andmebaas;
- 3) koostada raamstruktuur ja valida vajalikud matemaatilised vahendid, mis sobiksid nii toote kvaliteedi tagamiseks toote projekteerimisel kui ka kvaliteedijuhtimise korraldamiseks;
- 4) kavandada meetodika sünergiapõhiseks kvaliteedijuhtimise käsitlemiseks;
- 5) luua sünergiapõhine raamistik, mis võimaldab integreerida toote kvaliteedi ja kvaliteedijuhtimise kontseptsioonid, et aidata ettevõtteid kvaliteedijuhtimissüsteemide sertifitseerimiseks valmistumisel.

Uurimistöö esimeses osas on läbi viidud põhjalik kvaliteeditagamise süsteemide analüüs, haarates kaasa nii kvaliteedimõtlemise kujunemise, kvaliteedistandardite väljatöötamise kui ka kvaliteedisüsteemide sertifitseerimisest tuleneva majandusliku kasu analüüsi.

Töö teine osa on keskendunud kvaliteedijuhtimissüsteemide sertifitseerimisel avastatud inimlike vigade ja eksimuste olemuse uurimisele. Inimlike eksimuste ja vigade andmebaas on koostatud rohkem kui 200 ettevõttes läbi viidud sertifitseerimisprotsessi analüüsi põhjal. Andmebaasi analüüsi tulemusena järeldub, et inimfaktori mõju on otstarbekas käsitleda sünergiapõhiselt.

Kolmanda osa peamiseks eesmärgiks on leida sobivad meta-tasandi vahendid, mis aitaksid integreerida toote projekteerimise kvaliteedi ja kvaliteedijuhtimise kontseptsioonid ühtseks tervikuks. On jõutud järeldusele, et kvaliteedialase informatsiooni esitamiseks ja analüüsiks sobivaim vahend on sõltuvuste struktuuri-maatriksite (DSM) tehnoloogia. Samas on toote kvaliteedi ja kvaliteedijuhtimissüsteemi kontseptsioonide integreerimise ajalise ja etapilise raamistikuna sobivaim valdkondade (TDD) teooria. On leitud ka otstarbekas matemaatiline vahend, mis võimaldab prognoosida kvaliteeditagamise protsesside kestust.

Töö viimane osa on pühendatud toote kvaliteedi ja kvaliteedijuhtimise kontseptsioonide integreerimisele. Toote projekteerimise kvaliteedi poolel on testitud

valgustite projekteerimise sünergiapõhist meetodikat. Kvaliteedisüsteemide poolel on tõestatud nende sünergiapõhise käsitluse otstarbekus. Edasi on kavandatud terviklik raamistik projekteerimise kvaliteedi ja kvaliteedijuhtimissüsteemide sünergiapõhiseks integreerimiseks tagamaks toote tervikliku kvaliteeditagamise.

Töö tulemusena on jõutud järgmistele järeldustele:

1. Uurimisrühma kogemus interdistsiplinaarsete süsteemide kavandamisel on näidanud, et sobiv meta-vahend projekteerimise kvaliteedi ja kvaliteedijuhtimissüsteemide integreerimiseks on sünergiapõhine lähenemine. On kogetud, et enamik olulisi kvaliteeditagamise parameetreid nagu toote mõjusus, töökindlus, inimfaktorite mõju, turusituatsioon jms on käsitletavad sünergiapõhiselt.
2. Kvaliteedijuhtimissüsteemide sertifitseerimisel koostatud inimfaktorist tingitud vigade ja eksimuste andmebaasi alusel on kavandatud efektiivne meetodika ettevõtte enesehindamise läbiviimiseks enne kvaliteedijuhtimissüsteemi sertifitseerimist. Selle meetodika kasutatavus on kontrollitud sertifitseerimise tulemuste järeldustega.
3. Empiirilised uuringud on näidanud, et enamikku projekteerimise käigus ja kvaliteedijuhtimissüsteemide avastatud inimlikest vigadest ja eksimustest saab käsitleda sünergiapõhistena. Kehva projekteerimise põhjuseks on peamiselt segadused meeskonna liikmete omavahelises kommunikatsioonis, häired meeskonna liikmete sisemises sünergias või ebapiisav kompetentsus.
4. Struktuurimaatriksite (DSM) tehnoloogia on suurepärane vahend interdistsiplinaarsete süsteemide ja kvaliteedijuhtimissüsteemide modelleerimiseks. Tänu sellele, et DSM tehnoloogia võimaldab esitada maatriksi sisendite seoseid kompaktselt, visuaalselt ja analüütilises esitluses, on see igati soodne keskkond sünergiapõhise lähenemisviisi rakendamiseks. DSM tehnoloogia võimaldab prognoosida ka toote projekteerimise ja kvaliteedijuhtimise protsesside ajaliskulgu.
5. Teiseks kõrgema taseme vahendiks sünergiapõhisel lähenemisel on süsteemiteoorias lähtuv valdkondade teooria (TDD), mis on sobilik ajast ja tegevuste etappidest sõltuva raamistiku loomisel võimaldamaks kontrollida kvaliteedijuhtimisprotsessi käigu.
6. Sünergiapõhise meetodika testimine valgustite kui interdistsiplinaarsete süsteemide projekteerimisel reaalses tööstuskeskkonnas näitas, et meetodika on sobiv konkurentsivõimeliste toodete kavandamiseks. Sünergiapõhine lähenemine projekteerimisele avab võimaluse toote kvaliteedi tagamiseks alates selle kavandamise esimestest etappidest ja seetõttu on see sobilik komponent integreeritud kvaliteeditagamise süsteemi loomiseks.
7. Integreerides DSM tehnoloogia ja TDD põhimõtted on loodud sobiv keskkond toote kvaliteedi ja kvaliteedijuhtimissüsteemide integreerimiseks. Selles keskkonnas on kavandatud ettevõtte töötajate kompetentsi ja ekspertteadmiste tasemest lähtuvad adapteeruvad meetodikad, sünteesimaks neile omane algoritm sünergiapõhiseks kvaliteeditagamiseks. Viimase eelduseks on sünergiapõhiste optimeeri-

misvahendite kasutamise oskus, kompenseerimaks erinevate protsesside vajaka-jäämisi ja võimendamaks nende ühist kasulikku mõju, et suurendada positiivset sünergiat.

Hinnates käesoleva doktoritöö tulemuste uudsust tuleks siin välja tuua kolm momenti. Esiteks on välja pakutud uus sünergiapõhine lähenemisviis kvaliteeditagamisele. Selleks on koostatud unikaalne inimlike vigade ja eksimuste andmebaas, mis on kogutud tootmisettevõtete sertifitseerimisprotsessides. Selle põhjal on esmakordselt näidatud, et inimfaktori mõju kvaliteeditagamisel saab käsitleda sünergiapõhiselt. Teiseks on inimlike vigade ja eksimuste andmebaasi alusel kavandatud uudne enesehindamise meetodika, mis aitab ettevõtteid valmistada kvaliteedijuhtimise süsteemi sertifitseerimiseks. Kolmandaks on tõestatud, et integreerides sõltuvuste struktuurimaatriksite (DSM) tehnoloogia ja valdkondade (TDD) teooria on võimalik luua efektiivne sünergiapõhine kvaliteeditagamise keskkond. Selles keskkonnas on loodud uus perekond adapteeruvaid kvaliteeditagamise meetodeid, kus sünteesitud tegevusalgoritm põhineb meeskonna kompetentsusel ja ekspertteadmistel.

Käesoleva doktoritöö tulemuste uudsust on korduvalt testitud rahvusvahelistel teadusfoorumitel. Enamik konverentsidele esitatud töödest on karmides konkurent-sitingimustes loetud sobivateks suuliste ettekannetena, mis tõendab, et uurimustöö tulemused on originaalsed ja pakuvad laiemat huvi.

Hindamaks töö edasisi arenguid tuleb rõhutada kahte aspekti. Kuna kehva toodet põhjustavate tehniliste ja inimlike vigade ning eksimuste omavahelist piiri on toodete projekteerimisel uuritud küllalt põhjalikult, tuleks edaspidi neid uuringuid laiendada kogu kvaliteeditagamise süsteemile. Ka inimlike vigade ja eksimuste piir tavaolukorras ja füsioloogilise väsimuse ja stressi tingimustes on küllalt hägune. See on keerukas valdkond, mis vajab tulevikus töö- ja arstiteadlaste kaasamist. Teiseks puuduvad veel vajalikud kriteeriumid, mille alusel määrata neid sõltuvusi maatriksites, mis vajavad sünergiapõhist optimeerimist ja seni tugineb see valik peamiselt intuitsioonile.

ABSTRACT

The present thesis is focussed on the research of human shortcomings in the quality assurance environment. The driving force behind this research is to find an effective way for fighting against the so-called “bad” engineering. The basic idea for research is the conviction that most of quality problems can be treated as human-based resulting from human faults and mistakes.

The aim of the present research is to develop a synergy-based framework for quality management integrating it with the concept of engineering design quality into an overall effective quality assurance system. To solve the above described problem the research method first presumes composing a representative database of human shortcomings in the framework of quality assurance. The results side of the research looks for a synergy-based approach to the quality management system in order to make effective use of the information on human shortcomings to raise the capability of the company to prepare for ISO certification.

In the first part of the research an analysis of quality management systems is provided where in addition to stepping up quality thinking, the development of quality standards and the economics of quality certification are analyzed. As a result of the analysis the idea of the integration of the so far somewhat disunited quality management systems and the concept of product quality is put up.

The second part of the thesis is devoted to the investigation of human shortcomings which have become evident during the certification process of quality management systems. The database of human shortcomings of more than 200 production companies is completed. The analysis of this database resulted in comprehending the synergy-based conception of human shortcomings.

In the third part of the thesis the search for a suitable systems’ engineering tool for the integration of the concepts of product design quality and quality management is provided. The conclusion has been reached that the Dependency Structure Matrix (DSM) is the most suitable technology for the presentation and processing of quality information. Among time and stage dependent integration tools the Theory of Design Domains (TDD) is proved to be the most capable. This part of the thesis ends with a search for the mathematical tools for the probabilistic prognosis of the timing of quality assurance activities.

The last part of the thesis is fully devoted to the integration of product and quality management concepts. Special attention is paid to the testing of the synergy-based approach in the design of light fittings. Further the synergy-based approach is applied to empower the quality management system. Finally a complete framework for quality assurance is completed by the synergy-based integration of the concepts of engineering design quality and quality management. As a result of the research a capable tool for preparing quality management systems of production companies for ISO certification is proposed.

Keywords: product development, product quality, quality management, quality assurance, synergetics, synergy-based optimization.

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LIST OF PUBLICATIONS

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

1. Hindreus, T. and Reedik, V., Synergy-Based Approach to Quality Assurance, 13 p. (Paper is accepted for publication in proceedings of Estonian Academy of Science, Journal of Engineering)

2. Hindreus, T., Martin, A. and Reedik, V., Synergy-based Design of Light Fittings, In: Proceedings of NordDesign 2008, held on August 20-22, 2008 in Tallinn, Estonia, TUT Press, Tallinn, 2008, pp. 29-38.
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7. Hindreus, T. and Reedik, V., Quality Dimension in Complexity Management of Product Development Interaction Patterns, In: Proceedings of International Conference NordDesign 2002, held on August 14-16, 2002, Trondheim, Norway, Norwegian University of Science and Technology, 2002, pp. 129-136.
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8. Hindreus, T., On Implementing Product Development and Quality Management Systems, In: Proceedings of the 7th International Symposium on Machine Design, OST-2001, held on October 04-05, 2001, Tallinn, Estonia, Royal Institute of Technology Publications, 2001, pp. 109-115.
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9. Hindreus, T., Kannelmäe, Ü. and Reedik, V., Current Trends in Estonian Product Development Environment, In: Proceedings of the 2nd International Conference of DAAAM International Estonia, held on April 27-29, 2000, Tallinn, Estonia, TUT Press 2000, pp. 73-76.
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10. Hindreus, T. and Reedik, V., Quality Concept in Product Development in Conditions of Transitional Economy, In: Proceedings of the First International DAAAM Conference, held on September 25-27, 1997, Tallinn, Estonia, TUT Press, Tallinn, 1997, pp. 16-19.
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12. Hindreus, T., Design for Quality and European Community Directives, In: Proceedings of the First National DAAAM Conference in Estonia, "Science'95", held in September, 1995, Tallinn, Estonia, TUT Press, Tallinn, 1996, pp. 34-39.
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Elulookirjeldus

1. Isikuandmed

Ees- ja perekonnanimi: Tiit Hindreus
Sünniaeg ja -koht: 15.09.1963, Pärnu
Kodakondsus: Eesti

2. Kontaktandmed

Address: Purje 1A, Tallinn
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3. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (kraad/eriala)
Tallinna Tehnikaülikool	1999	Tehnikateaduste magister, Tootearendus
Tallinna Polütehniline Instituut	1989	Diplomeeritud insener. Masinaehituse tehnoloogia, metallilõikepingid ja instrumendid
Pärnu 1. Keskkool	1982	Keskharidus

4. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Eesti	kõrgtase
Inglise	kesktase
Vene	kesktase
Soome	kesktase

5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
04. 2006	Koolitajate koolitus, 2 päeva IRCA lektoritele, BVQI, Taani.
03. 2005	OHSAS Juhtaudiitori kursus, 3-päevane, BVQI, Eesti.
10. 2002	Läbirääkimiste oskused, 3-päevane kursus, Taani.
04. 2002	Juhtimisoskused, 5-päevane kursus, Fintra, Soome.
09. 1999	Keskonnajuhtimissüsteemide juhtaudiitori kursus, 5-päevane, BVQI, Soome.
07.1996	Kvaliteedijuhtaudiitorite kursus, 5-päevane, BVQI Soome.

6. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
06.1996 – tänaseni	Bureau Veritas Eesti OÜ	Juhataja
09.1989-09.2002	Tallinna Tehnikaülikool	Lektor
03.1995-05.1996	Kuninglik Tehnikaülikool, Rootsi	Teadur
03.1991-12.1991	Rauma Yards, Soome	Konstruktor

7. Juhendatud lõputööd

Teema	Aasta	Institutsioon/kraad/nimi
Erinevate juhtimissüsteemide ja täiuslikkuse mudeli kasutamise dünaamika Eesti ettevõtetes	2005	Tallinna Tehnikaülikool, M.Sc., Tarmo Mäesalu
Kvaliteedi- ja tootearendussüsteemide arengu analüüs Eesti tööstusettevõtteis	2003	Tallinna Tehnikaülikool, M.Sc., Artur Puusemp

8. Teadustöö põhisuunad

Kvaliteeditagamise, kvaliteedijuhtimissüsteemide.

Curriculum Vitae

1. Personal data

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 Date and place of birth: 15.09.1963, Pärnu
 Citizenship: Estonian

2. Contact information

Address: Purje 1A, Tallinn
 Phone: +37256567650
 E-mail: tiit.hindreus@gmail.com

3. Education

Educational institution	Graduation year	Education (degree/field of study)
Tallinn University of Technology	1999	M.Sc. Mechanical Engineering.
Tallinn Polytechnical Institute	1989	Diploma Engineer Technology of machinery, machine and cutting tools
Pärnu Secondary School No. 1	1982	Secondary education

4. Language competence/skills (fluent; average, basic skills)

Language	Level
Estonian	fluent
English	average
Russian	average
Finnish	average

5. Special Courses

Period	Educational or other organisation
04. 2006	Training of trainers, 2-day training for IRCA tutors, Denmark.
03. 2005	OHSAS Lead auditor course, 3-day IRCA registered course, Estonia.
10. 2002	Negotiating skills, 3- day course, Denmark.
04. 2002	Leadership training, 5-day course organized by Fintra, Finland.
09. 1999	EMS lead auditor course, 5 days EMS lead auditor training, IRCA registered auditor training course, BVQI, Finland.
07.1996	QMS lead assessor course, BVQI, Finland.

6. Professional Employment

Period	Organisation	Position
06.1996 – up to present	Bureau Veritas Eesti OÜ	Country Manager
09.1989-09.2002	Tallinn University of Technology	Lecturer
03.1995-05.1996	Royal Institute of Technology, Sweden	Researcher
03.1991-12.1991	Rauma Yards, Finland	Designer

7. Supervised thesis

Title	Year	Institution/degree/name
Dynamics of Implementation of Different Management Systems and Excellent Model in Estonian Enterprises	2005	Tallinn University of Technology, M.Sc., Tarmo Mäesalu
Quality Management and Product Development Systems Analyse in Estonian Enterprises	2003	Tallinn University of Technology, M.Sc., Artur Puusemp

8. Main areas of scientific work/Current research topics

Quality Management and Assurance.

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

1. **Jakob Kübarsepp**. Steel-bonded hardmetals. 1992.
2. **Jakub Kõo**. Determination of residual stresses in coatings & coated parts. 1994.
3. **Mart Tamre**. Tribocharacteristics of journal bearings unlocated axis. 1995.
4. **Paul Kallas**. Abrasive erosion of powder materials. 1996.
5. **Jüri Pirso**. Titanium and chromium carbide based cermets. 1996.
6. **Heinrich Reshetnyak**. Hard metals serviceability in sheet metal forming operations. 1996.
7. **Arvi Kruusing**. Magnetic microdevices and their fabrication methods. 1997.
8. **Roberto Carmona Davila**. Some contributions to the quality control in motor car industry. 1999.
9. **Harri Annuka**. Characterization and application of TiC-based iron alloys bonded cermets. 1999.
10. **Irina Hussainova**. Investigation of particle-wall collision and erosion prediction. 1999.
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13. **Igor Penkov**. Strength investigation of threaded joints under static and dynamic loading. 2001.
14. **Martin Eerme**. Structural modelling of engineering products and realisation of computer-based environment for product development. 2001.
15. **Toivo Tähemaa**. Assurance of synergy and competitive dependability at non-safety-critical mechatronics systems design. 2002.
16. **Jüri Resev**. Virtual differential as torque distribution control unit in automotive propulsion systems. 2002.
17. **Toomas Pihl**. Powder coatings for abrasive wear. 2002.
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23. **Medhat Hussainov**. Effect of solid particles on turbulence of gas in two-phase flows. 2005.
24. **Frid Kaljas**. Synergy-based approach to design of the interdisciplinary systems. 2005.
25. **Dmitri Neshumayev**. Experimental and numerical investigation of combined heat transfer enhancement technique in gas-heated channels. 2005.
26. **Renno Veinthal**. Characterization and modelling of erosion wear of powder composite materials and coatings. 2005.
27. **Sergei Tisler**. Deposition of solid particles from aerosol flow in laminar flat-plate boundary layer. 2006.
28. **Tauno Otto**. Models for monitoring of technological processes and production systems. 2006.
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31. **Jaan Kers**. Recycling of composite plastics. 2006.
32. **Raivo Sell**. Model based mechatronic systems modeling methodology in conceptual design stage. 2007.
33. **Hans Rämmal**. Experimental methods for sound propagation studies in automotive duct systems. 2007.
34. **Meelis Pohlak**. Rapid prototyping of sheet metal components with incremental sheet forming technology. 2007.
35. **Priidu Peetsalu**. Microstructural aspects of thermal sprayed WC-Co coatings and Ni-Cr coated steels. 2007.
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37. **Andrei Dedov**. Assessment of metal condition and remaining life of in-service power plant components operating at high temperature. 2007.
38. **Fjodor Sergejev**. Investigation of the fatigue mechanics aspects of PM hardmetals and cermets. 2007.
39. **Eduard Ševtšenko**. Intelligent decision support system for the network of collaborative SME-s. 2007.
40. **Rünno Lumiste**. Networks and innovation in machinery and electronics industry and enterprises (Estonian case studies). 2008.
41. **Kristo Karjust**. Integrated product development and production technology of large composite plastic products. 2008.
42. **Mart Saarna**. Fatigue characteristics of PM steels. 2008.
43. **Eduard Kimmari**. Exothermically synthesized B₄C-Al composites for dry sliding. 2008.
44. **Indrek Abiline**. Calibration methods of coating thickness gauges. 2008.