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Synergy-Based Chaos Control in the Multi-Agent Hierarchical Systems

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

Rommi Källo

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MEHHANOTEHNIKA E103

Sünergiapõhine kaose juhtimine paljuagentsetes hierarhilistes süsteemides

ROMMI KÄLLO

TTÜ
KIRJASTUS

CONTENTS

ABBREVIATIONS

APEX - Agile Project Management Execution
CNC - Computer Numerical Control
CPS - Cyber-Physical Systems
DCS - Distributed Control System
DSM - Design Structure Matrix
EVM - Earned Value Management
FAT - Factory Acceptance Test
HAZOP - Hazard and Operability Study
HMI - Human Machine Interface
IIOT - Industrial Internet of Things
IO - Input and Output
LHS - Latin Hypercube Sampling
MAS - Multi-Agent Systems
MPC - Model Predictive Control
OGY - Ott, Grebogi, Yorke (chaos control methodology)
PC - Personal Computer
PID - Proportional, Integrative and Derivative
PLC - Programmable Logic Controller
PPF - Proportional Perturbations Feedback
RTU - Remote Terminal Unit
SAT - Site Acceptance Test
SCADA - Supervisory Control and Data Aquisition
SIL - Safety Integrity Level
SIT - Site Integration Test
STS - Social-Technological Systems (systems which include technological and human and organizational components)
TDD - Theory of Design Domains

INTRODUCTION

Background and focus of the doctoral research

Today's fast development of science and technology has led to information society where the information and knowledge transfer, its processing and the overall speed have become the most important trends. The technologies have reached a new development stage empowered by growth of electronics, computer technology and automation for control of the production plants, buildings, agriculture, traffic, trade, etc. (Medida, 2008). As a result, the philosophy of the production has changed too. Self-learning robots, intelligent machine tools and instruments, model predictive control (MPC), multiagent systems (MAS), remote monitoring and wireless communication are examples of the machines of new generation. Modern industrial control systems have been developed to be more universal, capable of controlling different types of equipment. These requirements include also reconfigurability, responsiveness and flexibility (Seilonen et al., 2009). At the same time, every specific factory needs a specific automation system to be configured on the basis of some universal system (Jämsä-Jounela, 2007). Process automation helps to enhance product quality, control the whole range of products, improve process safety and plant availability, efficiently utilize resources and lower emissions (Jämsä-Jounela, 2007).

In today's reality, automation systems have become increasingly complex. The amount of data and variables circulating in these systems has grown enormously. New technologies, including wireless networks, fieldbus systems, optimization algorithms, analytics solutions, cloud computing and asset management systems, boost the efficiency of process control systems. 4th generation Industrial Revolution (Industry 4.0) is based on the Cyber-Physical Systems (CPS), the transformative technology connecting physical assets to computational technology (Lee et al., 2014). As a result, the process control systems are moving towards big data handling to enable fast decision-making for improved productivity (Lee et al., 2014).The latest technologies developed under the umbrella of Industry 4.0 are focusing on smart factories, devices and systems that are linked and intercommunicate and make decisions based on information, similarity comparison and artificial intelligence built into the systems. All the industrial devices would be connected to the Industrial Internet of Things (IIoT) and have intelligence built into them to communicate directly with other devices and systems. As a result, the automation system design becomes complicated and costly and the reliability and quality problems arise.

The reliability of a system depends on the reliability of its individual components, component interactions and execution environment. The area of technical reliability is very well studied and is outside focus of this PhD research. But another aspect of reliability is present, which varies depending on how the system is designed and used (Palviainen et al., 2011). At the operation of the process control system, many reliability problems depend on human skills and shortcomings. Because a human factor is a key figure in the development and design of a multi-agent system, it is necessary to address socio-technical problems through organization psychology and teamwork development.

Resulting from the situation described above, a new wave of research into the role of human shortcomings emerged at the beginning of the present century (Blessing, 2003; Eppinger, 1997; Hindreus and Reedik, 2002). The management and improvement of skills and competences in a decentralized organization is becoming increasingly important (Jämsä-Jounela, 2007). Increasing complexity of knowledge and information has created the need of their structuring and ergonomical visualization (Tergan and Keller, 2005). Profound analysis of trends in the project management research has shown that under pressure of customers, relevant research is targeted to the direction of Agile Project Management Execution (APEX) (Spiropoulos, 2015). Dynamic computerized modeling of large factories enables development of the process during its operation, training of the operators for handling abnormal situations; thus, preventing the problems during production and increasing the availability of the production facilities. Therefore, the need for systems engineering is growing and systems quality problems need to be solved with a focus on the system performance quality.

Quality assurance methods and practice is an area well covered. Despite that, a grey area of interpretation of the role of human shortcomings exists (Hindreus, 2009). During the start-up of new (or renovated old) factories, much time and finance is spent to solve the human-related errors and faults. At the same time, the need for decreasing start-up costs is increasing due to the market pressure. New equipment, systems and applications are introduced frequently, while under market pressure, the time for their exhaustive study is decreasing. Analysis of testing and start-up data of real process automation systems shows that negative synergy due to human shortcomings is of high occurrence, which can increase the start-up costs of the factories by up to 5–10 % . Further, finding and eliminating the problems takes much time and causes delays on factory start-up. The concept of the present thesis has resulted from the described situation.

In this PhD research, the author of the thesis has benefited a great deal from his 17-year industrial experience of design and commissioning of automated factories. Originality of this approach is based on the reality that the information about the shortcomings from automated factories start-up is made strictly confidential by the systems suppliers and factory owners and therefore is not available in the academic research literature. The firm basis of the research is a reality database of empirical studies of human shortcomings in industrial control system development projects. The existence of such a database gives confidence about “bad” engineering and authenticity of the results obtained by theoretical research developed on this basis.

Research methods and positioning.

The area covered in this thesis is the teamwork and communication methodology applied to the design and commissioning projects of the automation systems of large industrial plants. This research differs from the actual project management technologies. The difference lies in the focus, which addresses the problems hindering the beginning of the project and during the project execution, i.e. human shortcomings – faults, mistakes and strategic miscalculations. The basis for the research is a unique database covering the shortcomings in the preparation, design, commissioning and start-up of new or renovated production plants automation systems, which includes 26 factories from all over the world collected since 1999 by the author of the thesis.

Theoretically, the problem area of the doctoral research belongs to the field of chaos control. The process of hierarchical transfer of information from one team to another in scheduled time is very sensitive to tainted information (Ivancevic et al., 2008; Mikhailov et al., 2001). In such multi-agent distributed artificial intelligent systems, agents' decisions depend on those made by the agents upper in the information flow. If the agents use tainted on imperfect information, they tend to make poor decisions. In summary, it leads to the chaotic behavior of downwards agents and downgrading of the performance of the whole system (Ivancevic et al., 2008). Thus, human shortcomings can cause real chaos in the process automation design and commissioning process. This obstacle makes the whole system extremely complicated and nonlinear, where it is possible to achieve useful solutions only using soft computing tools. As the outcome of the present research, an optimal strategy of tracking, hindering and blocking the dissemination of human shortcomings has to be developed.

The basic research philosophy in the present doctoral thesis is the synergetic approach to the design and commissioning of automated factories. This is a follow-up to the successful use of this philosophy by the research group during twenty years. Traditionally, subjects such as information, communication, automation, optimization, production and business handled separately are nowadays conflating, allowing benefits from seamless interaction and increasing synergy. By synergistic analysis and improvement of the teamwork and communication pattern by recommendations, a remarkable amount of resources are expected to be saved. The synergy-based approach to start-up difficulties in the present research field is new and original, enabling an analysis of the real reasons of start-up problems and planning the use of measures to avoid them. Therefore, decreasing the factors of negative synergy and increasing positive synergy is a very important measure for reducing the design and commissioning costs.

The present thesis continues in its pursuit previous doctoral research in the field of synergy deployment by the research group at Tallinn University of Technology (TUT) led by Prof. V. Reedik. The research efforts of this group have focused on the following problems: to uncover the essence of negative synergy followed by the development of an adaptive methodology for synergy-based design of interdisciplinary systems and further application of synergy-based approach to quality assurance. The contribution of the current thesis will be to employ the synergy-based approach to the process automation system design and commissioning. Figure 1 shows the position of the thesis research in the research group activities.

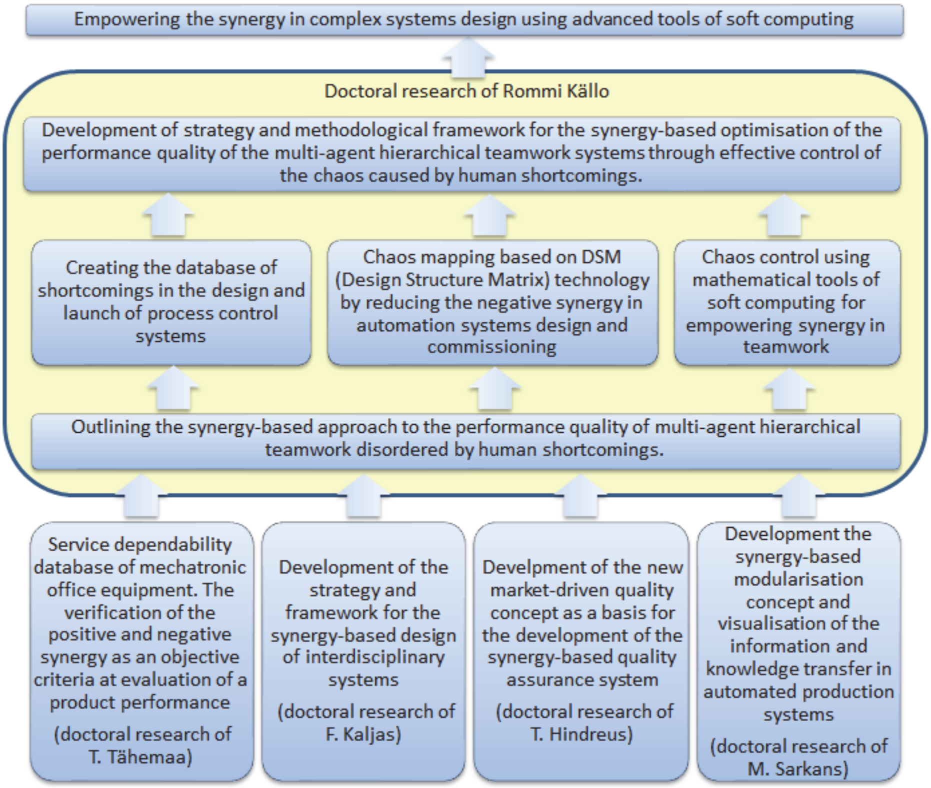


Figure 1. Structure of the current thesis and integration with the previous research.

The new approach has to be scalable for different sizes of the projects and teams, utilizing the best practices of teamwork, cooperation, technical know-how distribution and result-oriented approach.

The main **keywords** of the present research are: industrial control systems, teamwork management, chaos control, synergy deployment, design structure matrix, discrete event modelling, project duration prediction, project management.

The results of the doctoral research have been published in three key publications that are related directly to the present thesis. Altogether there are six publications in the area of the thesis research. The results of the research have been presented on three international conferences. Judging from the discussions that followed, the subject area of the thesis has been of theoretical and practical interest.

In summary, the objective of the present doctoral thesis is to outline the synergy-based approach to empower the performance quality of multi-agent hierarchical teamwork systems disordered by human shortcomings. The object of the research is the design and commissioning process of industrial automation systems. An expected research outcome is a methodology of a probabilistic prognosis and strategy for the reduction of the project duration. An initial basis of the research is an empirical study of the human shortcomings in the real industrial automation systems design and commissioning teamwork that grants also novelty of the research results.

The final research hypotheses and research tasks are described after the literature review in section 1.6.

1. OVERVIEW OF THE RESEARCH OF COMPLEX SOCIO-TECHNICAL SYSTEMS OPTIMIZATION

The first task is to study the state of art in the key areas of the present research: automation technology, teamwork organisation, synergy deployment, quality assurance etc. Focus here is on the constraints in the automation systems design and commissioning. Next, tracking and hindering the chaos in multi-agent hierarchical teamwork, the main focus of the present research, are addressed. Special attention is paid to synergy deployment, an integrating factor of the present thesis. A substantial part of the survey is the search for suitable mathematical tools needed for the planned PhD research.

1.1 The constraints at process control system design and commissioning

Present global trends on the industrial control systems market are efficiency, quality and flexibility of production and production systems. In the automation technology, several new approaches to process control are under development, mostly connected with information and knowledge transfer and usage. At the same time, the process control systems developed are targeted to multi-agent systems consisting of autonomous decision makers that communicate, negotiate and co-ordinate their work automatically to achieve the final goal (Bussmann et al., 2004; Weiss, 1999).

From the multiple definitions for the word "*system*", it is appropriate to choose the most suitable to characterize the topics of the present research. It is better to define it as *"an organization of parts that are connected together to form a functioning machine or an operational procedure"* (Patrick and Fardo, 2009). From this point of view, process control systems are applied to a large section of industry that deals with things that have direct influence on the manufacturing of finished products (Benson, 1997). In this context, all this involves a manipulation of a variety of process variables in order to realise total automatic control (Patrick and Fardo, 2009).

Automation systems must be modelled to have more information about the physical processes available for the process control systems from the beginning. For this purpose, MPC (Model Predictive Control) models are being integrated to DCS (Distributed Control System) control logic to enable continuous optimization of the process. MPC technology is developed today to be a part of the multi-level hierarchy of control functions (Qin and Badgwell, 2003; Manenti, 2011). To be more efficient, today's process control system needs to be reconfigurable which means a capability to adapt to system configuration changes. The system must be responsive to handle various operational conditions and to be flexible to produce different products and handle a variety of control operations (Seilonen et al., 2009). Cyber-physical systems containing physical assets combined with computational capabilities increase the complexity of system configuration (Lee et al., 2014). As a latest innovation of the 4th industrial revolution (Industry 4.0), the focus of the developments is on the Smart Factories, products and services integrated in the Industrial Internet of Things (IIoT) (Stock and Seliger, 2016).

Today's market situation is characterized with increased competition between the product's vendors, growing complexity and constant change with decreasing investment (Bussmann et al., 2004). In these conditions, it becomes increasingly important to have a process control system operating reliably, predictably within the profitability range, giving bigger output of better products and using less energy (Benson, 1997). Despite the fact that process control systems are physically similar for different production processes, the process functions depend highly on the type of the process (Isermann, 2011). Current research is focusing on the power and process systems. Author of this thesis has started his career as an engineer of process control system projects. During the 17-year advancement, the author has been working as a lead engineer, project manager and automation manager for large automation projects in different parts of the world.

Systemwise there are not many different philosophies of process control systems to use: DCS (Distributed Control System), PLC (Programmable Logic Controller), HMI (Human-Machine Interface), SCADA (Supervisory Control and Data Acquisition), or Hybrid Controller.

DCS systems are known for their analogy regulatory control capability and redundancy (Shaikh, 2009). DCS architectures were essentially orientated towards the main control room as a marshalling point for long instrumentation cables for the input and output signals. Systems were then based on proprietary components: operating systems, control networks, automation system hardware, and software configuration tools with all the hardware located centrally in control facilities. Process control was mainly isolated to a certain number of controllers for control logic: PID (Proportional, Integral and Derivative) control loops to control temperature, pressure, steam, and flow; measurement loops to read the process data from instruments and binary loops to control motors, pumps and valves and to read signals from various switches and sensors in the field. Today's DCS systems can be implemented in a cost-effective way in a single (or redundant) microprocessor-based controller. Some of the fieldbus based technologies, such as Foundation Fieldbus, additionally support the concept of "Control in the Field," where a single, independent control loop can be implemented in the field far away from the main controller (Medida, 2008).

PLCs emerged as a replacement to the relay control systems. Before PLC control, sequencing, and safety interlock logic for manufacturing processes was accomplished using hundreds of relays, cam timers, drum sequencers, and dedicated closed-loop controllers (Sharma, 2011). DCS and PLC technologies initially served two different control requirements. Nowadays the combination of DCS-PLC system is widely used, DCS being the main control system, handling core processes and PLC controlling some sub-processes. These integrated systems have been expanded vertically with IT-systems and horizontally with intelligent drives, motors, process instrumentation and discrete control technologies (Shaikh, 2009). The comparison of control modes for DCS and PLC systems is presented in Fig. 1.1.

HMI/SCADA systems offer mainly the same capabilities as DCS, but they offer a more open solution as there are no dedicated hard- and software requirements (Merritt, 2008). This solution allows more flexibility and possibility for faster changes, but at the same time, requires a more qualified personnel and a continuous development process. HMI/SCADA system does not support the Fieldbus solutions.

Hybrid control originally meant connecting programmable logic controllers (PLC) to DCS systems (Herb, 2007). Nowadays in can be a combination of DCS, PLC, RTU (Remote Terminal Unit) and Personal Computers (PC). It is quite common practice today to combine different products and solutions together according to the process specialties and technology requirements (Sharma, 2009).

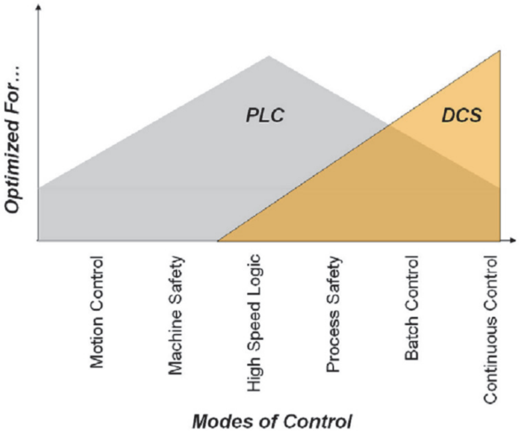


Figure 1.1. Comparison of control modes (Shaikh, 2009).

The process control system reliability is one of the most important factors during factory operation. It is highly dependent on the reliability of the components used to build up the automation system, interactions between the units, data communication and software. System deployment is the first design step where the reliability of the automation system or its parts can be optimized (Meedeniya et al., 2011). Reliability is the quality to be evaluated not only in the hardware components of the process automation system, but also in software packages. Reliability in our case can be defined as a probability of failure-free operation of a system for a certain period of time in specific environmental conditions (Rodrigues et al., 2005; Lin, 2012). Reliability can be approached as a quality over time (Sun et al., 2008). As one unreliable element can disable the whole system, the critical components must be evaluated for reliability before integration to the process control system. In reality, the impact of faults on reliability is different because of different usage profile of the automation system (Palviainen et al., 2011).

With the increasing complexity of production plant control systems, the probability of human shortcomings is increasing due to the growing number of communication activities and component sophistication (Fagade et al., 1998). The key figure in systems engineering, design and commissioning is the human beings with their cultural, educational and technical backgrounds and organizational behaviour. As a project is not continuous in duration, a team with certain tasks and responsibilities formed is a temporary organization by nature (Turner and Müller, 2003). Overall, it is changing with the change of the project size and it incorporates temporary resources with permanent employees as Client, Supplier or Partner companies (Sydow et al., 2004). Multi-agent automation system projects require specific skills and competences (Huemann et al., 2007). Due to the temporary nature, the hierarchical teamwork system of the project is more dynamic and involves more uncertainty in a discontinuous environment (Huemann et al., 2007). The project management philosophy has changed from technical to human project management (Turner and Müller, 2003) or more specifically, team management (Delisle, 2004). In the project team, one person can hold multiple roles; at the same time, this can cause role conflicts at an individual level (Rau et al., 2002).

Due to the above reasons, complexity of an automation system project is increasing from an engineering point of view, the systems are constantly changing and investments are decreasing due to the market pressure (Bussmann et al., 2004). The amount of data and variables circulating in the systems has enormously increased. Accordingly, the systems engineering effort is growing as a result of increase in system complexity (Samad, 2007). The technical background described above has increased the importance of engineering competence and communication (Kaljas et al., 2004) substantially.

Beginning from 1996, research team of Tallinn University of Technology has been focused on a synergetic approach for the integration of technologies in the interdisciplinary systems, considering also socio-technical factors during design and application. Over the years, specific databases have been collected from different fields of technology (see Fig. 1.2), which have built a solid background for the analyses of human shortcomings.

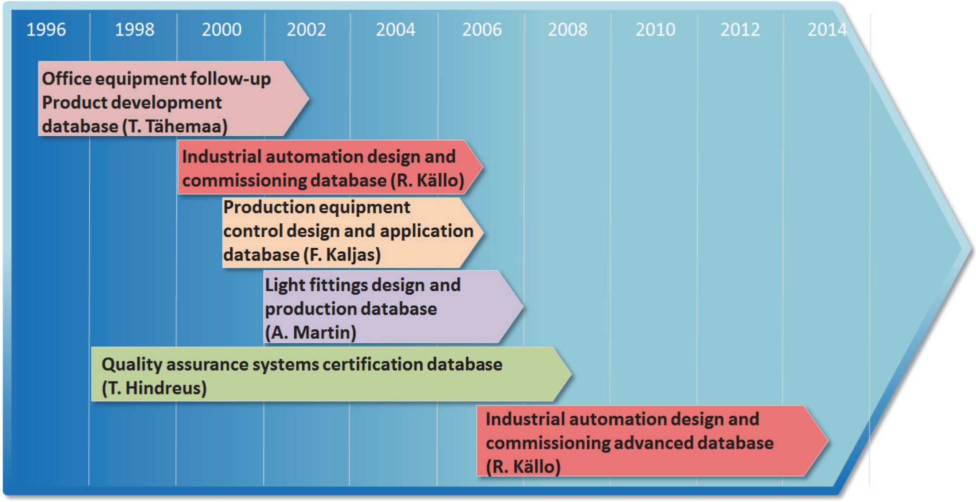


Figure 1.2. Development of databases of human shortcomings by the research team. The names of responsible team members are given in brackets.

Author’s everyday work practice has shown that the human shortcomings in the socio-technical hierarchical teamwork system are the main reasons of losses of resources at the start-up of new automated factories, reaching up to 5–10 % of the labour cost during the whole project. This is an average appraisal summarized from 26 industrial control systems design and commissioning projects provided under the consultancy of the thesis author. Thus, to reduce the enormous losses, it was required to analyze the reasons in detail and find ways to bring this abnormal situation under control, which at the same time, created grounds for the present doctoral research.

1.2 Chaotic coherent collective dynamics in teamwork

The industrial process automation project is also a highly interactive social process involving many people and teams for working with several sub-disciplines making millions of coupled decisions (Eppinger and Salminen, 2001; Tang et al., 2010). The sequence of the progress of process automation design starts with the drafting of the general description of the required system, followed by a detailed task description for the real system configuration and a factory acceptance test, continued by commissioning in the final location. To run the project, a consultant company is usually hired for integrating all the technical workforces of the project and commissioning groups. After receiving final documentation from the process suppliers, the automation supplier starts system configuration, application software programming, human-machine- and process interface implementation. The actions above end with careful Factory Acceptance Test (FAT) before delivery to the production plant and integration with the physical equipment delivered by process suppliers. After successful installation and tests, the activities continue with commissioning, where new members are introduced into the project team.

The activities above compose a complex hierarchical system where the information of completed tasks is transferred between the teams within the carefully scheduled time. Such a multi-agent distributed artificial intelligence system is very sensitive to tainted information transfer (Ivancevic et al., 2008; Mikhailov et al., 2002). An agent's each decision inevitably depends on the decisions made by an agent upper in the information flow. In case of using tainted or imperfect information, agents tend to make poor decisions (Krishnan et al., 1997; Gralla and Hermann, 2014). This leads to the chaotic behaviour of agents using the information and downgrading the performance of the whole hierarchical teamwork system. As a result, human shortcomings may cause real chaos (see Fig. 1.3) in the control system design and commissioning, making the whole system complicated and nonlinear. Therefore the chaos control is the central issue in the present research.

The chaos theory and control, a wide area of research that is advancing fast, has already a long history. First, it is necessary to determine the position of the current research on the very complex field of chaos control, stretching from cells to societies (Mikhailov and Calenbuhr, 2002). On the one hand, the generic mechanism of growing chaotic behaviour in the framework of industrial control system project design and commissioning belongs to the field of chaotic dynamics of binary systems since all the decisions in these systems result from neural networks activities. At the same time, realisation of these decisions is similar to spatio-temporal chaotic dynamics, where the hierarchical system is lacking long-time and large distance coherence in spite of organised local behaviour (Manneville, 2005). Because of human faults and mistakes, the chaotic trajectories must be corrected by iterations and the rework and the chaos control system must have the feedback nature. As the third factor, the task is stochastic or random since human shortcomings are predictable only by statistical data collected during the realisation of industrial process control projects. Therefore, the corresponding unique database is a cornerstone of this thesis research (see Chapter 2).

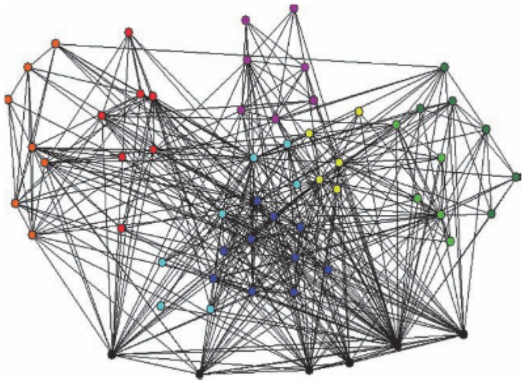


Figure 1.3. Communication network node-link diagram, visualisation of a chaotic system (Eppinger and Browning, 2012).

Thus, the bundle of initial conditions makes it complicated to position the present research, but it is clear that it belongs to the category of the hierarchical model of complex coherent actions (Mikhailov and Calenbuhr, 2002). However, it has very close connections to other neighbouring classes such as mutual synchronisation and dynamic clustering from a lower level and dynamics and evolution of a higher level. Resulting from the careful study of the literature, it is concluded that no readymade solutions for the present research in the field of chaos theory and control are available. Thus, the main task is to find useful guiding rules and solutions suitable for pursuit of the present research.

History of the chaos theory goes back for over a hundred years, when the 3-body problem (Sun, Moon and Earth) presented by Isaac Newton was investigated by Henri Poincare. He was the first to present a mathematical description of chaotic behaviour in a dynamical system in his Prize Memoir (Barrow-Green, 1997). Special mathematical procedures have later been developed to understand the unpredictability and irregularity of nonlinear systems (Ivancevic et al., 2008).

Chaos is a complex behaviour of a simple, well-behaved deterministic system, where its aperiodic performance depending on initial conditions, makes prediction of system behaviour impossible (Strogatz, 1994). Chaotic behaviour arises in noise-free simple systems, which are naturally deterministic; so there is randomness and determinism at the same time in the same system (Hilborn, 2000). Interactions between agents in complex distributed systems are forming many stationary and time-dependent patterns. The chaotic patterns are uncorrelated and consist of many irregular elements and can be influenced by internal or external noise (Mikhailov et al., 1991).

The chaos is normally an undesirable behaviour of the system, which should be avoided or controlled if avoiding is impossible. Controlling of chaos by converting chaotic behaviour of agents to that of regular using minimal effort allows maximizing the output of the dynamic system and reaching predefined objectives in the planned time (Ivancevic et al., 2008). Typically, chaos should be decreased to minimum or suppressed (Cheng et al., 1998). But chaos may be useful under certain circumstances like in fluid or gas mixing processes and heat transfer. However, reducing "bad" chaos or raising "good" chaos, there is anyway a need for its control (Cheng et al., 1998).

A basic nature of a system's chaotic behaviour is its critical dependence on the initial conditions. Due to that and the fact that initial conditions are never known exactly, the chaotic systems are naturally unpredictable. The trajectory predicted from initial conditions differs from the real trajectory exponentially in the course of time (Ivancevic et al., 2008). Chaos control is possible by introducing stabilizing perturbations to the system, which move the process trajectory closer to the desired one. Small perturbation can cause a significant change in the course of time if introduced at the correct time and in an appropriate place and the system can produce a number of desired dynamical behaviours (Boccaletti et al., 2000). An important concept in the chaos theory is the butterfly effect when a small change can cause a large deviation in the results (Ivancevic et al., 2008). This is the most promising concept to be used in the present research.

E. Ott, C. Grebogi and J.A. Yorke introduced the idea of chaos control called OGY in 1990 (Ott et al., 1990). This method of chaos control is stabilizing unstable periodic orbits by applying carefully selected perturbations to the system to create desired dynamics (Ivancevic et al., 2008). Feedback methods use the intrinsic characteristics of a chaotic system like the sensitivity to initial conditions for stabilizing the orbits, which already exists in the system. Non-feedback algorithms at the same time use the small perturbing external force (Lakshmanan, 1997). As a modification of OGY, the proportional perturbations feedback (PPF) control was introduced to fix the timing of external agitators. This was stabilizing the trajectories to periodic instead of irregular spikes seen in the uncontrolled system. This method is known as blind chaos control (Kaplan, 2000).

Optimal control algorithm is a method of chaos control by introducing a small perturbation from an external interaction field. This would guide the chaotic behaviour to the average trajectory. However, it is important to keep external interaction small as a large attractor could cause additional chaotic motion (Botina et al., 1995). The method of following the fixed trajectory tries to keep the chaotic trajectories around predefined fiducial trajectory.

The spatio-temporal chaos control is based on interacting waves in excitable media, which commonly annihilate on colliding. There are several mechanisms of such breakup as meandering on the spiral focus where the wave collides with itself and breaks up, creating multiple smaller spirals. This continues until the spatial part of the system is spanned by several spiral waves that activate different regions (Schöll and Schuster, 2008; Ivancevic et al., 2008).

The chaotic behaviour of the analyzed teamwork system is in critical dependence on its initial conditions by means of agent's decisions. When planning the system, every agent's decision has a trajectory (orbit) and time period for fulfilling the task. However, in a chaotic system, the real trajectory is different from that predicted and the distance between these increases exponentially in time. Controlling the chaos moves the trajectory towards a predicted trajectory and produces a number of wanted dynamical states (Boccaletti et al., 2000; Ivancevic et al., 2008).

Resulting from the described literature research, it is reasonable to develop further studies in two main directions. First, it is necessary to find an environment for exhaustive description and visual representation of the relationships of the agents in the project working groups and formulate initial conditions in theory. It seems promising here to use the matrix correlation method for the dynamic behaviour of stochastic financial markets (Mantegna, 1999). Secondly, the stochastic nature of the hierarchical process needs some modelling technology for the evaluation of time-dependent processes. In the modelling of any system, first, the problem of treatment of the agent with its complexity of relations and stochasticity emerges. The agent in a teamwork system can be treated as a discrete automaton with stochastic dynamics (Mikhailov and Calenbuhr, 2002). It is possible to define this automaton with a limited repertoire of responses as they act in their working process (not fully expressing their complexity). Thus, it is possible to model the interaction and behaviour of an active agent as a dynamic and evolutionary network in the class of hierarchical organisations. This opens the way to describe the "strength" of agents' interactions and to take into account the synergy of these relations (Eppinger, 1997; Kaljas, 2005; Hindreus, 2009).

1.3. Search of relevant research tools

To find proper tools for analysing the complexity of project execution and tracking and hindering the faults and mistakes, it is necessary to describe the structure of this socio-technical system and find ways to decompose it to manageable units. In section 1.2, it was shown that the industrial process control system design and commissioning is hierarchical. The key to rational design and commissioning process management in such systems is to order the communication between the agents and agents' teams properly, taking into account the peculiarities of hierarchical systems. Hierarchical organization is quite common in its nature. There are two kinds of hierarchies: evolutionary and dynamic. Evolutionary hierarchies are based on filiation (see Fig. 1.4), where the agnation describes a distance between the elements in the hierarchical trees forming an ultrametric space similar to genealogical trees (Rammal et al., 1986). The coexisting structures interacting dynamically in hierarchies in different levels are forming dynamic hierarchies (Mikhailov and Calenbuhr, 2002). The last is close to our task where communication forms the structural layer on top of the organisation, showing some self-organisation features, while dynamically influencing the hierarchical organisation.

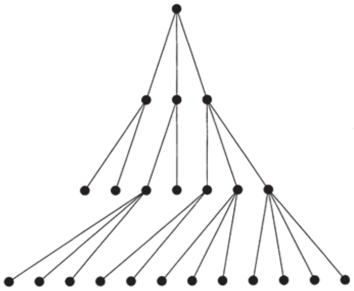


Figure 1.4. Graphical representation of the hierarchy from the point of information transfer ultrametrical distance (Mikhailov and Calenbuhr, 2002).

The present research is based on a process automation database collected from many large automated factories, which creates a firm basis for describing the dynamic behaviour of a special type of a hierarchical system. From the point of view of the analysis of this multi-agent socio-tehnical system, the most important feature in the hierarchical system is the decomposability. It allows describing the formation of the structure at a certain hierarchical level, which is influenced only by the forces at that particular level (Mikhailov and Calenbuhr, 2002). The timescale of the processes resulting from interactions is determined by the interactions intensity, where a more intensive interaction shortens the characteristic timescale of the process. However, there is no universal dynamic rule available for comparing and evaluating the strength of communication but some characteristics which determine the communication intensity are available.

For better understanding of the socio-technical hierarchical system as an organisation, it is required to be divided to simpler levels and these levels need to be classified. In our case, we can separate the organisation level and the communication level. The project organisation can be considered as a physical system due to the technical roles of team members, but it is also holding some aspects of a social system. In the case of a physical system, the structural hierarchy corresponds to their timescale hierarchy. Social systems dynamics grows with the size of the group in timescale. The timescales are different – slow processes in a high level are not interfering with the dynamics in a lower level. Also, low-level processes are not interfering with high level dynamics (Mikhailov and Calenbuhr, 2002). To optimise the hierarchical system, we need to find the factors and the timeslot that can be influenced by an external substance and the ways to push the structure of the system to the self-organisation in a desirable manner. Self-organisation of decomposable social systems is determined by interactions with the corresponding timescale in a certain level. In higher levels, elements of a lower level can be seen as simple objects with a few relevant properties. Accordingly, mathematical modelling of hierarchical patterns becomes possible. A hierarchical organization ties together complexity of dynamics, its stability and predictability. If a complex system is designed hierarchically, it starts to behave predictably and regularly (Mikhailov and Calenbuhr, 2002).

The communication, as a number of random processes in the project organisation, is causing certain chaotic behaviour (see section 1.2). These can be described by the statistical probability distribution of random events or sequences of events and trajectories (Mikhailov and Loskutov, 1991). Discrete random processes can be analysed by probabilistic automata, where the coming state of an event cannot be predicted because of chaotic dynamics in the system. When the system’s state is described by some continuous characteristics vitiating in time, it can be handled by the continuous random processes theory. To determine the probability of a specific trajectory, the probability density function can be used (Mikhailov and Loskutov, 1991).

Certainly, the communication between the team members plays an important role in the project execution period. The key of efficient communication procedures lies usually in the hands of project and team managers, but also other team members influence the realization of communication procedures. The communication planning starts with organisational structure planning, and is followed by developing a communication plan and lines of communication (Zulch, 2014). The communication in the automation project team can be represented without using trajectories of ultrametrical distances but by direct communication links between project team members.

In the search for a suitable tool for describing human relations and grouping communication procedures on the basis of their cooperation capabilities, the network modelling technique of the Design Structure Matrix (DSM) has proved to be most suitable. The DSM technology allows us to develop, design, manage and visualize the complex relations between all team members (Eppinger, 1997). It is easy to understand the relationship patterns due to the effective compact visualisation. The powerful analysis package includes the graph theory, matrix mathematics and some specialised DSM methods (Eppinger and Browning, 2012). The DSM suits for this research due to its high flexibility and a wide range of modelling possibilities. DSM has been used for a long period to manage complex engineering projects, handle components and their interactions as architecture of organisation or structure, communication, activities, relationships and information flows. The TUT research team has successfully used DSM for many years for empowering synergy in office machine design, control system design for production equipment, at light fitting design and production as well as in quality assurance systems transformation. Therefore, DSM tools seemed appropriate for use in this research.

The Design Structure Matrix technology was introduced in the 1970s by Professor D. Steward (Steward, 1981). He was the first to use the square-matrix format to describe the network of variable interactions for the design process. The method was developed from earlier sequenced systems where it was required to solve the mathematical equations with minimal iteration (Eppinger and Browning, 2012). The first industrial applications of DSM matrixes were introduced in the 1990s (Eppinger et al., 1990). The Steward's DSM was improved with static models, clustering analysis and some applications in the organisation and product domain (Eppinger and Browning, 2012). Since then, the use of DSM has become increasingly popular due to the capabilities of handling the interactions of the structure's components (Pimmler and Eppinger, 1994; Suh, 1990). It is easy to introduce the synergetic relation dimension into this system.

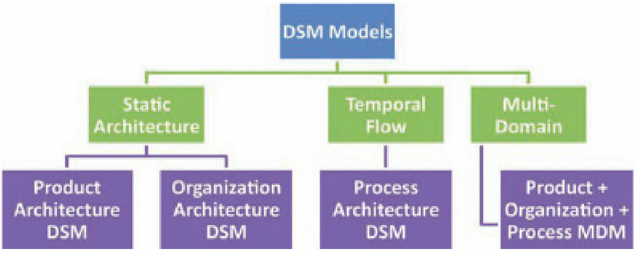
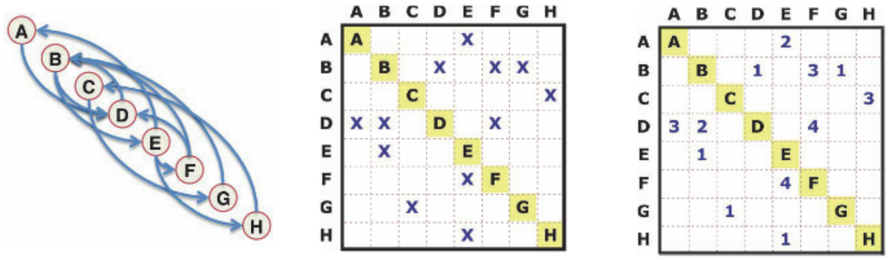


Figure 1.5. Four types of DSM models (Eppinger and Browning, 2012).

DSM uses a five-step approach to the system modelling and analysis – decomposing to break the system into elements, identify to mark the relationships, analysis to rearrange the structure, display to represent the model graphically, and improve to take the steps towards effective communication scheduling (Eppinger and Browning, 2012). This allows us to approach the chaos control in the socio-technical hierarchical system in a structured way and gives a possibility to decompose the dynamic hierarchy to manageable substructures. The DSM models are classified into four different types in three categories (Figure 1.5). In our case, the Organisational Architecture DSM is an suitable model. DSM allows organising the communication flows between the agents, and finding possible iteration loops. The partitioning by the Boolean matrix operation based on the graph theory and developed by Warfield (1973) finds the optimal communication schedules and groups identifying the dependencies in the matrix structure (Cho, 2001).

A major advantage of using DSM is the graphical visualisation of the square matrix structure, which makes the system architecture easily readable. The DSM can be of a binary type, indicating only if the interaction is present or not, but can be extended with additional attributes indicating the type, strength, importance or impact of interactions (Eppinger and Browning, 2012).



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

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

a) b) c)

Figure 1.6. Representation of a system in a) diaphragm form, b) binary DSM and c) numerical DSM (Eppinger and Browning, 2012).

To minimise the time and costs for the implementation of an industrial control system project, we need to plan the communication as effectively as possible. Thus, it is necessary to form suitable teams based on required communication and cooperation and also define needed communication levels. As a result, we should be able to minimise the shortcomings of communication, find the critical areas where the occurrence of faults and mistakes is higher, and find the way to hinder occurrences of shortcomings.

The tools above are essential to find an approach to the problems in a synergy-based way. The main purpose of the synergy-based analysis of multi-agent processes is to find a management philosophy for highlighting and amplifying positive synergy and preventing discrepancies caused by the negative synergy in the teamwork processes.

The tools described enable us to structure the project organisation as a hierarchical system and bind the dynamics of communication into the hierarchical teamwork. It is then possible to visualise the socio-technical system for better understanding of the processes in different layers. The system can be extended by introducing the timescale to the project execution layout and then decomposing it to manageable subsystems. With the help of the DSM technology and discrete event modelling it seems possible to find the areas of tracking and hindering the faults and mistakes and work out the methods for minimising the difficulties during project execution.

1.4. Basics of synergetics and synergy-based optimization

The focus in this thesis research is on synergetic aspects of communication inside the project teams and in the hierarchical teams system. These teams are handled as socio-technical schemes acting in the framework of interdisciplinary technological environment. The aim of the thesis is to introduce the synergetic approach to the analysis of the hierarchical systems to track and hinder possible communication-related difficulties during project execution. Previous experiences of the TUT working group in the synergy-based approach applied to the interdisciplinary systems design and quality assurance have been successful. Thus, it is expected to be a suitable tool to solve the problems raised in the current thesis (Martin et al., 2006; Hindreus, 2009).

The concept of synergy was formulated already by Aristotle as “the whole is greater than the sum of its parts”. The word “synergy” originates from Greek , where syn (together) and ergon (work) are combined and used as “working together” or cooperation. Linguistically, the word “synergy” expresses the situation when the summary effect of different factors due to their mutual empowering is greater than their arithmetical sum (Oxford Dictionary). At first, “synergy” was defined as a positive outcome of any synergistic system. However, negative synergy cannot be neglected, it exists in parallel to the positive and the technical terms “positive” and “negative” synergy are quite common in the literature (Ballard, 2001; Tähemaa, 2002).

Synergetics as a separate science was founded by Hermann Haken in the late 1960s (Haken, 1983). In the beginning it was possible to explore synergy effects only by experimental research. This approach to quantitative synergy in technical equipment and processes has been accidental and time-consuming. On the qualitative side of synergy, the experimental research was predicated on searching for Ginzburg-Landau order or Haken’s enslaving parameters where system’s properties change radically (Haken, 2004; Mikhailov and Calenbuhr, 2002). This qualitative side of synergy has given remarkable results in physics, biology and other fundamental sciences. As the planning strategies of classical experiments exclude nonlinear dynamics from the beginning and therefore synergy in the analysed processes, these are useless in quantitative synergetics (Hindreus et al., 2010).

Synergetics handles complex nonlinear systems, which are usually combined from a number of smaller systems. These dynamic systems can be of different kind and have an ability of cooperation in a self-organizing manner (Haken, 1983). The results of synergy are widely applicable because close to the instability point, where the systems change their behaviour dramatically, the similarities occur in different systems in many application areas. According to the mathematical theory, in the neighbourhood of instability points, high-dimensional dynamics can be compacted to a low-dimensional dynamics, which is ruled by *order parameters*. The relation of components to order parameters is described as a *slaving principle* (Haken, 2004).

All the complex systems are influenced by the environment and these influences can be qualified by control parameters. The parameter change results in the smooth adoption or qualitative change of the system (Haken, 2004). In some circumstances, small changes introduced to the system increase the stability of the system and enhance the positive synergy (Corning, 1995). However, in other conditions, a minor perturbation can destabilise the system and this effect is known as "self-organised criticality" (Bak and Chen, 1991).

The definition of qualitative synergy is based on three main conditions: sharing, flexibility (error compensation) and task-dependence. The elements should all share a certain task, dynamically change the contribution to the task and change its functioning in a task-specific way (Latash, 2008). The quantitative synergy has a simpler nature: it can be evaluated in per cent metrics, where the 0-point marks the situation where no synergy is present.

To describe synergy mathematically, we need to start from the information about the states of every system part or system state vector (Haken, 2004).

$$q(t)=(q_1,\ldots,q_n,\ldots q_N), \tag{1.1}$$

where every component q_n represents the state value of a subsystem. If the subsystems are characterized by more than one value, the q vector depends also on the space and time:

$$q(x,t) \tag{1.2}$$

It is assumed that the equation of the state vector motion is a nonlinear differential stochastic equation in the form of

$$\frac{dq}{dt} = N(q,\alpha) + F(t), \tag{1.3}$$

where N is nonlinear function in the deterministic part of the equation and F is the stochastic part.

The result of the synergistic approach here can be spelled out in the following way. It is possible to reduce a high-dimensional system to a low-dimensional one when it is close to the instability point using the slaving principle

$$Q_n(t)=f_n(\xi(t);t), \tag{1.4}$$

where f_n is a time-dependent function only via fluctuation forces F, as otherwise it is determined by the order parameters ξ.

The order parameters submit a low dimensional dynamics

$$\frac{d\xi(t)}{dt} = \check{N}(\xi, \alpha) + \dot{F}(t) \tag{1.5}$$

Here $\dot{F}$ is the fluctuation forces that may or may not depend on the order parameters ξ (Haken, 2004).

One way to reduce the influence of human faults and mistakes in a cooperation project is to optimize the decision-making process. The difficulties in the decision-making procedure start from insufficient and incomplete information about the problem. Also, the time factor is important, as decisions need to be made in critical situations and in a short time. In a complex nonlinear system, there is usually discrepancy between the data required and the data available that are needed to make a decision, i.e. there is a certain amount of unknown data. As shown in the simplified figure (Fig. 1.7), a variety of possibilities exist to fill the gaps of unknown data. Certainly, different decisions can be made even when all the data are known (Haken, 1997).

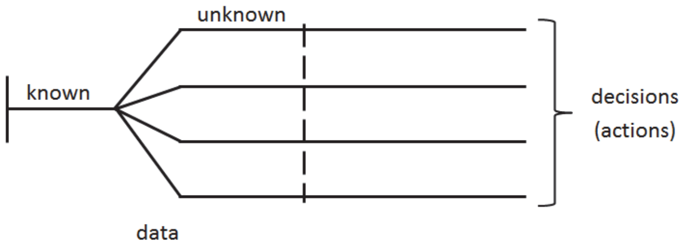


Figure 1.7. Different ways to complement known data (Haken, 1997).

In the decision-making process, there are similarities with pattern recognition. In both cases, the pattern is recognised or the decision is made using a similarity measure. Decision-making for some action is based on a certain amount of data, communication, teams, individuals, and their cognitive psychology and interests. All this forms a set of different decisions, which all are governed by their specific order parameter. Order parameters have different strengths and the competition between possible decisions is won by the strongest order parameter. The strength of the order parameter can come from a known pattern or one or more specific stronger arguments in the initial set of inputs (Haken, 1997). This creates theoretical grounds for increasing synergy in the teamwork.

The ground for positive synergy is hidden in the optimization in its wider interpretation. Over the years, optimization was focused on the results of logical optimization in the engineering design. The success of analytical optimization is sensitive to the knowledge of the physical processes and the quality of logically educed structures. Gaining physical synergy at the cooperation of different technologies predicates full understanding of the essence of integrated processes to make these processes fully controllable (Kaljas, 2005). In this context, the problem of evaluation of strength and parametrical side of synergy effects occurs. It is clear that in a linear world (1+1+1=3), no synergy can exist. Synergy belongs to a nonlinear world (1+1+1><3). So, the only evaluation possibility is relative evaluation, as seen from Fig. 1.8.

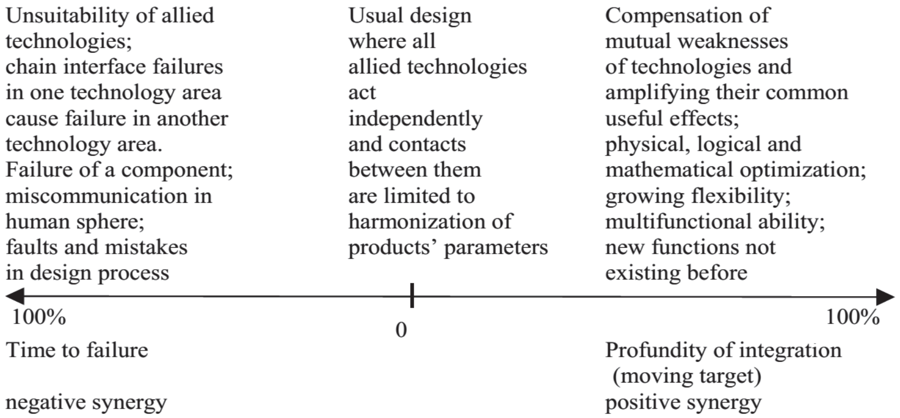


Figure 1.8. Positive and negative synergy deployment for product design (Kaljas, 2005).

The synergy-based approach to interdisciplinary systems design developed from the 1990s in the TUT Department of Machinery under the supervision of Prof. V. Reedik consolidates reliability problems, design parameters, market situation, human factors, etc. with the multi-agent systems teamwork optimization (Fig. 1.2). However, the synergy-based physical optimization was first used by the research team at the end of the 1960s for the development of the high-accuracy pneumatic interruptible jet sensors (Leschenko et al., 1972; Neve and Reedik, 1975). The synergy studies were restarted by T. Tähemaa in his doctoral research (Tähemaa, 2002). The quantitative characteristics of negative synergy in an infant mortality period of the new launched product have been thoroughly studied and determined (Tähemaa et al., 2002). It was found that the positive synergy is the result of compensation of mutual deficiencies and boosting the useful effects between the allied technologies. On the basis of an office equipment service database, it was shown that negative synergy is a reality and plays an important role during the product's first steps in the market (Tähemaa, 2002). The absence of synergy in teamwork may lead to high probability of a failed product as a result of "bad" engineering. Infant mortality period of new product models called forth a new look at the design procedures with the customers involved in the design process.

The following research was focused on the role of human shortcomings in equipment control system design and production. Integrating Design Structure Matrix (DSM) technology and Theory of Design Domains (TDD) enables a detailed analysis of the synergy-based design process. A case-study of the design of pneumatic positioning device successfully proved the efficiency of the new approach. As a result, the new concept of interdisciplinary system design was developed adapted to the capabilities of the design team (Kaljas, 2005). Further, the synergy-based approach was extended to the quality management systems and focused on the human-based shortcomings in quality assurance and in the quality certification of production companies. A new family of synergy-based quality assurance tools was developed, where the combination of the decision-making algorithm is based on the competence and know-how of the team (Hindreus, 2009). Then, the synergy-based approach to design platform products with early evaluation of their modularity was developed by M. Sarkans (Sarkans, 2012). A common feature of all the studies mentioned is that the system's behaviour is described by the DSM technology.

The next logical step was return to the problem areas of the present thesis, i.e.to the study of the role of human shortcomings in the hierarchical multi-agent systems, started already in the author's MSc thesis (Källo, 2004). Naturally, due to the time distance caused by the professional duties abroad, new approaches were required and the problem areas were enriched with growing professional experience.

1.5. Conclusions of Chapter 1

1. From an engineering point of view, automation project complexity is increasing due to new technologies, solutions and approaches to the multi-agent control systems. At the same time, the impact of human mistakes and faults is escalating over a time. Analyses of the results of project execution have shown that possible losses from human shortcomings cause 5–10 % extra labour costs during the project. This is too high and the only way to reduce it is to find ways of enhancing the quality of the automation systems design and commissioning process.

2. The industrial process automation project is an interactive hierarchical social process of communication and decision-making. The project execution is composed of many decisions made in the project teams in different hierarchical levels, each decision depending on the decisions made in the upper level of information flow. In case of imperfect or tainted information, lower agents make poor decisions, which leads to a chaotic behaviour of the whole system. Chaos control is an inevitable measure to avoid the spreading human faults and mistakes during project execution.

3. The chaotic dynamics of binary systems and spatio-temporal chaotic dynamics seem to be a useful environment to describe the processes in a hierarchical teamwork system. The chaotic behaviour of a dynamic teamwork system is dependent on the agent's decisions where every decision has a trajectory and a time period in the system. The real trajectory may differ from that expected and the distance between them may increase as a function of time. By controlling the chaos it is possible to move the trajectory towards the desired one.

4. The structure of the socio-technical hierarchical teamwork system is useful to analyse under the umbrella of the hierarchical organisation theory. It is necessary to find a suitable environment for describing and visualising the relationships between the agents in project teams and formulating the initial conditions and evaluating interactions weight with the synergy criteria to these information flows. The DSM (Design Structure Matrix) tools seem to be most useful for analysing the system and specially finding ways of tracking and hindering the human faults and mistakes.

5. Synergy-based optimisation has been used for integration of technologies considering also socio-technical factors. The stochastic nature of the hierarchical process needs some modelling technology to evaluate the time-dependent processes. It seems that using discrete event modelling and soft computing, suitable areas for introducing synergy effects into the system can be found.

1.6 The research objective, hypotheses and tasks

The objective of the present doctoral thesis is to outline the synergy-based approach to empowering the performance quality of multi-agent hierarchical teamwork systems disordered by human shortcomings. The object of the studies is the industrial automation systems design and commissioning process. The target is approached by the analysis of the database of empirical studies, mapping of the current situation and finding ways for increasing synergy in teamwork.

The **hypotheses of the present doctoral research** consist of the following assertions:

1. In a hierarchical multi-agent system, similar to the environment of industrial automation project realisation, tainted information due to human shortcomings - faults, mistakes and strategic miscalculations – leads to chaotic behaviour of downward agents and growing chaos in the whole system.
2. To prevent growing chaos, it is reasonable to use the Design Structure Matrix (DSM) technology that enables us to optimize the teamwork integration by forming task-oriented metateams and scheduling communication in dynamic temporal teamwork.
3. It is possible to develop a prognosis methodology of the project duration utilizing discrete event modelling and the database of human shortcomings as a basis.
4. Using proactive chaos control by mapping its trajectories and well-timed dynamic empowering of the synergy level by reasonable rework and tuning, it is possible to attain remarkable reductions in project time and cost.

To attain the objective, three basic tasks have to be solved:

1. To provide empirical research of human shortcomings in the industrial automation systems design and commissioning process.
2. To evaluate potentiality of the chaos control methods in the multi-agent hierarchical teamwork and to propose the strategy of tracking, hindering and blocking the disturbances caused by human shortcomings.
3. To develop a methodological framework for timing the project execution based on the statistics of human shortcomings and find ways for reducing the project time at their accidental arise.

The objective of the first task is to create a unique statistical database of human shortcomings disclosed during the professional activities of the author at the design and commissioning of the process automation projects. An advanced classification of human shortcomings here is a necessary precondition. This database is serving as a foundation to evaluate the outcomes of the present research.

The aim of the second task is to bind the previous empirical research with the chaos control and find possible ways for tracking, hindering and blocking the human shortcomings dissemination in the multi-agent hierarchical teamwork. Successful prevention of growing chaos in multi-agent systems depends on the effective mapping and decomposition of the growing chaos.

The third task is to develop an optimal timing methodology for the process automation project design and commissioning taking into account the statistics of human shortcomings. In addition, it is necessary to propose a strategy and tactics of reducing the project duration at the arrival of accidental human shortcomings during project execution.

The contents of the present thesis may seem to deviate from the classical structure of the thesis. The reason lies in its problem-orientated nature and generalistic pattern.

2. RESEARCH OF HUMAN SHORTCOMINGS IN INDUSTRIAL AUTOMATION PROJECTS

2.1 Environment of empirical research

Studies of enhancing human cooperation efficiency are based on the reality database resulting from the empirical analysis of human shortcomings. Such a unique database gives evidence of authenticity and applicability of the theoretical research results. Since 1999, the author has been compiling an authentic database of human shortcomings at the design, testing and commissioning of large-scale process automation systems covering information from 26 new and renovated production facilities on four continents. The factories remain unidentified due to sensitiveness of the subject. From the production point of view, these factories belong to five main groups:

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

The heart of the hybrid process control systems of all these projects is the Distributed Control System (DCS). All of the process control systems consist of several PLCs for certain equipment or subsystems control, programmable frequency converters for variable speed pumps and motors and some contain also additional Remote Terminal Units (RTU). The author of the thesis and his team has been actively involved in these projects in different positions: as an engineer, project manager or automation manager. The database contains the analysis of reasons, solutions and labour-consuming weight of the faults, mistakes and bad decisions discovered during the project execution.

To understand the process of project execution of a factory control system, an overview of the project schedule is presented in Fig. 2.1. Chronologically, the process of industrial plant automation system design starts from the drafting of the general concept of operational principles, followed by particularizing specific requirements and system architecture for system configuration purposes. Next, detailed design activities are composed, followed by the implementation of system and application software and the Factory Acceptance Test (FAT). After a successful FAT, the automation system is verified during the commissioning phase of the factory and the project is handed over to operation and maintenance.

From the project team point of view, the project begins with appointment of responsible persons in the owner's team to observe the construction of a new automated production plant or renovation of an old one in progress and to transfer owner requirements and competences into the project. The consultancy group is forwarding the owner's requests and needs to the process supplier(s) and collects the resound data from the process supplier(s), converts it to the applicable format, approves it with the owner and forwards the information to the automation supplier. A separate commissioning team is formed involving members from the project teams. The end users are usually part of the commissioning team, simultaneously under training to run the plant at the same time.

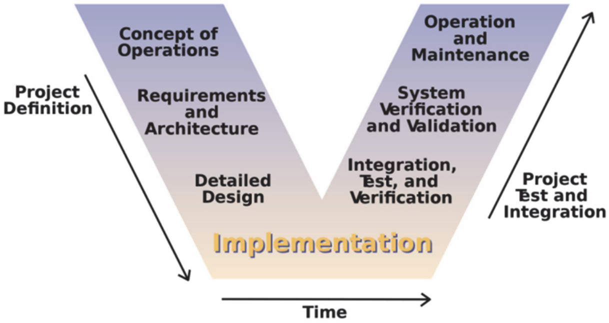


Figure 2.1. Theoretical V-model of a systems engineering process. (Osborne et al., 2005).

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

The architecture of an automation system is highly process-dependent. Nowadays factories use more centralized systems, where there is one distributed control system (DCS) for the main process and possible local controllers of sub-processes are connected to it. This approach enables us to use advanced DCS features for simpler controllers and field instruments (measurement device, actuator, motor, pump etc.). As the factory's availability is an important issue, redundant solutions for automation systems are often used. Redundancy can go down to an instrument level, covering all the equipment from the operator desk to the field devices, which on the other hand, requires large investments. The redundancy level commonly used is covering the DCS controllers and servers, for safety-critical systems also IO cards. Some critical instruments must be redundant also. There are a number of additional features and options available for process automation systems, including some for smoother operability, some for better data analysis and some for supervisory use. The nowadays trend of the automation system layout is to keep the computers out of the factory control room to reduce the noise and heat in the operator's workplace and dust from the automation system components. According to the Industry 4.0 approach, the cloud-based solution for data transfer, handling and storage is recommended, which reduces requirements for control system computer hardware (Stock and Seliger, 2016). In this case, additional measures need to be taken into account from a cyber-security point of view.

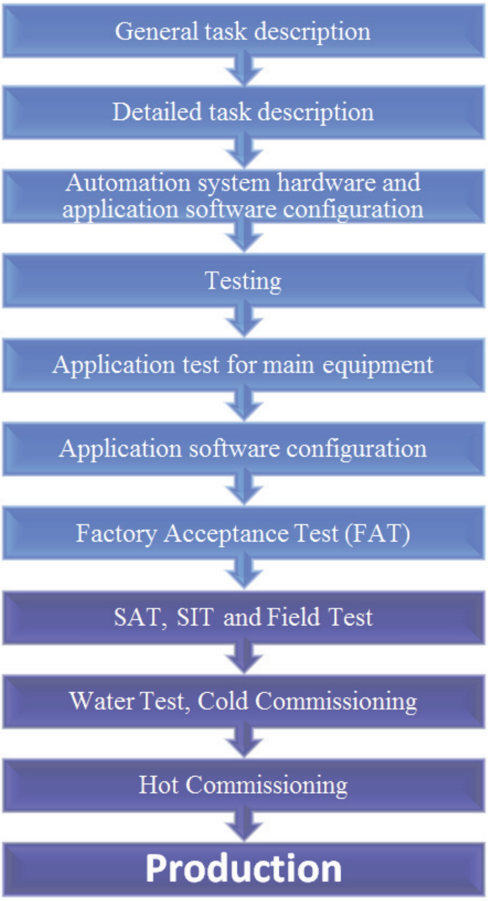


Figure 2.2. Chronological execution of a industrial control system project.

Figure 2.2 shows the phases of project chronological execution in detail. In the industrial control system project, first, the general design task and the basic requirements for the automation level and the control system extent are defined. Previous decisions are followed by a detailed task description, where the documentation for the system is prepared to be handed over to the automation supplier to start the design of the process control system. The documentation package for the industrial control system configuration is project–specific; however, for a good result, minimum requirements are to be fulfilled. The documentation should be finalised before system planning starts. However, to reduce the time for the project commonly the control system design starts in parallel with the detailed design documentation. Due to the sequencing of tasks, usually during (and after) the configuration phase, some revisions of the documents that need to be handled in the implementation process are appearing. Human-Machine Interface (HMI) design is considering factory operational specialty, plant layout, automation system architecture, operator's background, etc. There are several types of operator display configuration principles available in the market. The symbols used to indicate the equipment and instruments are mostly standardised. To reduce communication faults in multilingual working groups the text indications in displays is possible to use multiple languages, changeable online without interrupting the DCS work. The operator displays have usually hierarchies of four levels – overview displays, major process displays, detailed process displays, and selected detail displays (Bullemer et al., 2008). Alarms are the most important indications of process conditions, thus the concept of alarming is carefully considered in means of prioritizing and visualization. Poorly configured alarms can lead to major process disturbances and accidents. For an effective alarm handling, a variety of software tools are available in the market.

During the design phase, application software is tested by the application working group. For a more extensive test, the system design team and the end customer are participating. Depending on the results of the intermediate tests, the design team corrects possible design mistakes to prevent the escalation of chaotic trajectories further into the next project phases.

The process control system hardware and software are designed based on the previously described documentation and in tight communication between the project teams. This effort is evaluated during FAT (Factory Acceptance Test), where a comprehensive part of design phase shortcomings is discovered. FAT is necessary to carry out to prove that the application software is complex and the system architecture is built up according to the requirements. FAT is considered as an essential part of project execution and its main goal is to reduce the risk of time-consuming failures during Site Acceptance Test (SAT), Pre-commissioning and Commissioning. The FAT is normally initiated by end user and performed by the automation system vendor; consulting company, process designer and end user are to witness the test (EVS-EN 62381:2012). FAT is a test covering for all the automation system hardware, wiring, functions, visualization, operation, subsystems, and interfaces.

At the end of a successful FAT, the automation system is ready to be shipped to the factory and after the SAT and SIT (Site Integration Test), ready to carry out commissioning. During the SIT, the process control system connections to several independent subsystems are tested to ensure functionality and interoperability of all the systems operating together. The purpose of the SAT is to test that automation system hardware, software and physical installation are engineered according to the initial documentation and ready to start the commissioning phase. During the SAT, automation system communication is tested up to the system cabinets, IO (process Input and Output) cards and marshalling terminals; also, Ethernet- and power cabling, grounding and redundancy in all available levels are verified.

Commissioning starts with field tests (IO tests), where communication from the automation system to the field instrument is checked; also, calibration and movement of instruments are tested. As the field test is usually carried out sequenced by the process units, the commissioning of instruments with tested IOs starts in parallel. The commissioning is divided into two parts - cold and hot commissioning. During the cold commissioning, equipment items are tested one by one or in small groups with water as a process media or no process media at all. During hot commissioning, the plant is started up for the test production of the final product to tune the technological processes and to assure the product quality.

The purpose of commissioning is to finalize the project and bring the production process to its operational design parameters. During commissioning, every operational component of the production plant is tested, from an individual field instrument up to larger production systems. All the limit values are adjusted and controllers tuned to ensure a smooth and safe production process. Large amounts of data are analysed to optimize the process and make modifications where feasible. The commissioning phase is often used to train future plant operators. Usually, they start working with commissioning engineers and perform certain tasks to educate and train and familiarise themselves with their future operational tasks. The project execution steps can be slightly different depending on a specific project, but basic steps remain usually the same.

2.2 Methodology of empirical research

When analysing the effects of negative synergy at system design and application, the causality of failures emerges. In the first analysis of the database carried out up to year 2006, the human shortcomings were classified as human faults (misunderstanding each other and negligence) and as mistakes (lack of competence and absence of special knowledge) (Kaljas et al., 2004). For the present research, an advanced and more detailed database for 2006 – 2015 was compiled. Figure 2.3 shows an advanced classification of human shortcomings, the reason of which is that the environment and operating conditions of the human beings are changing. Therefore, strategic miscalculations were separated and additional criteria were provided for omitted procedures and systems integration disability. Thus, the changed conditions could be addressed in a more specific way. At the same time, it simplifies the utilization of corrective actions for blocking and hindering the difficulties during the project execution period. As a result, human shortcomings analysed in the above database were classified into three main categories – faults, mistakes and strategic miscalculations. Technical problems of reliability were handled as a separate category. An exact classification of human shortcomings contributes to a clear overview of possible measures to be taken for controlling the chaotic behaviour of the teamwork system.

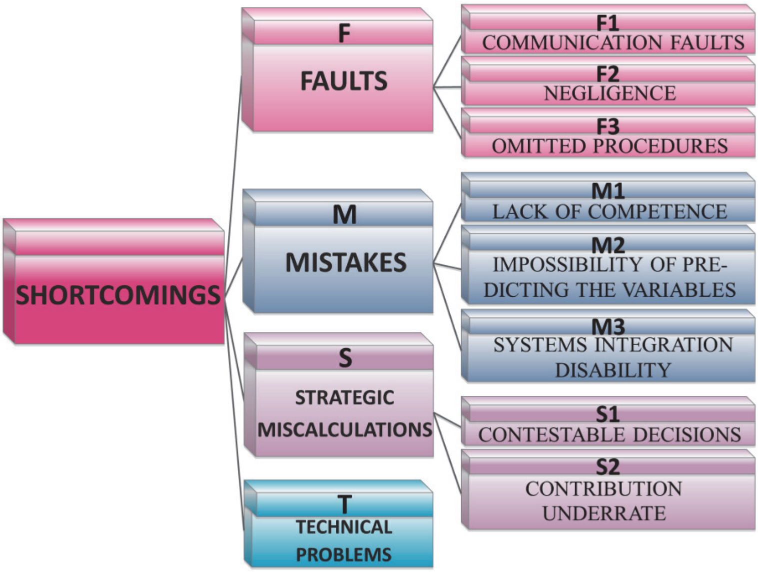


Figure 2.3. Advanced classification of human shortcomings.

Faults F are the prevalent shortcomings in the process automation development process. Reducing human faults is a key factor of the quality, reliability and system performance improvement and also the time and costs reduction during the project implementation.

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

F1 – Communication faults:

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

F2 – Negligence:

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

F3 – Omitted procedures

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

As the faults mentioned under each category are similar in nature, further classification to subcategories was found unnecessary.

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

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

M1 – Lack of competence:

- Lack of single team member competence;
- Insufficient support from other team members;
- Incomplete initial information about team members' competences and thus unreasonable allocation to tasks.

M2 – Impossibility of prediction of the variables:

- Unavailable competence in a specific area;
- The variables can be evaluated only during testing.

M3 – Systems integration disability:

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

Strategic miscalculations S are more cost-consuming shortcomings during the design and commissioning. Miscalculations are usually made before the work has started and it is difficult to influence them during the design or commissioning. To avoid these, it is required to use the synergy-based approach from the very beginning of the project.

There are two subcategories of strategic miscalculation to analyse the nature:

S1 – Contestable decisions:

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

S2 – Contribution underrate:

- Work plans scheduling problems;
- Overestimated evaluation of the efficiency of contribution;
- Unclear extent of needed work efforts.

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

The shortcomings database contains information of how the shortcomings were discovered. It may describe its symptoms rather than the real nature of the shortcoming. Therefore, a systematic analysis of the situation at the time of occurrence of a shortcoming is necessary to reveal its real reason. The database was deliberately analysed already during the data collection to ensure a comprehensive classification into the categories described above. After closing the database for supplementing, it was re-analysed in order to reconsider the classification, the source of shortcomings and trajectory during project execution.

2.3 Empirical research results of human shortcomings

2.3.1 During automation system design and FAT test

The main hindering and blocking zones for shortcomings are the tests of process control system operability and reliability – the FAT test and commissioning tests. Figures 2.4 and 2.5 show the quantitative share of certain shortcoming types found during the FAT and commissioning process, respectively. FAT is performed to find all the possible problems occurring during the design phase found at the simulation of the automation system. From the shortcomings discovered during that period, faults **F** (distribution of shortcomings in Fig. 2.4) form more than half of all the problems. These are usually clarified and fixed during the FAT; however, it hinders effective work during tests and leads to a rush at the end of FAT and/or problems with the time schedule. Communication faults **F1** (16.5 %) made during the project design phase are caused by poor communication where all necessary information is not transferred properly between the teams, which lead to solutions based on predictions. Items not discussed belong to this group where different team members understand the documentation in different ways, not synchronising the comprehension. Negligence faults **F2** (21.6 %) can be caused by copying the documents, application logic or HMI displays configuration, not paying sufficient attention to adapting the copied solution to a new use. It also covers the design or configuration work done in a hurry, not paying attention to all the details. Omitted procedures **F3** (17.3 %) cause the largest loss in time and resources, as insufficient initial information leads to additional rework. The common fault falling to category F3 is missing information in documents or not meeting the document delivery deadlines.

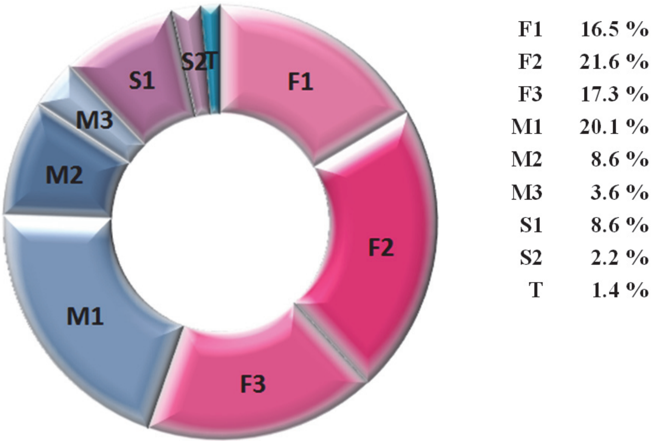


Figure 2.4. Statistics of human shortcomings discovered in the design of the process automation system and its FAT test. See the classification scheme in Fig. 2.3.

Mistakes caused by lack of competence **M1** (20.1 %) include insufficient personal competence undiscovered during the project work. The missing competence can usually be found inside of the team or company involved in the project and fixed rather efficiently. The mistakes of type **M2 -** impossibility of prediction of the variables (8.6 %) are more difficult to avoid and fix due to unavailable competence in this specific area or awareness that a specific kind of competence is required. The need for related modifications may arise during the testing of the subprocesses of specific application software. Solution of these problems requires a high level of overall technical competence and back-office support availability. System integration disability problems **M3** (3.6 %) are usually related to different levels of development in soft- or hardware. The development is everlasting and does not consider always all the areas of possible use of a specific item. Insufficient testing of different subsystems and equipment can end up with significant disadvantages regarding the effectiveness of the testing procedure and influence of the quality and time of FAT.

Share of strategic miscalculations **S** is rather small compared to previous categories but their financial impact for the whole project can be significantly higher. Contestable decisions **S1** (8.6 %) usually occur when work packages for specific teams are relatively large and a temptation arises to save resources in smaller sub-items. **S2** type of contribution underrate shortcomings (2.2 %) arise due to the market pressure and industrial investments dynamics, which leads to inability to schedule the work according to specific project needs. Inefficient scheduling or delays in some projects may lead to a need to work with several concurrent projects at the same time.

The percentage of technical errors **T** (1.4 %) is rather low, consisting mainly of automation system hardware failures.

The description of FAT procedures and results gives a detailed overview of difficulties found during the FAT and opens a possibility for further synergy-based analysis.

2.3.2 During the commissioning and start-up process

Commissioning is the last screen to find problems in the automation system testing with real process equipment, in which an attempt is made to regard all possible scenarios of process behaviour. During the commissioning, the distribution of shortcomings is slightly different from FAT problems, and reasons of those vary (Fig. 2.5). The largest group of shortcomings is faults **F**; however, not as domineering as in the statistics of the FAT test. The nature of faults is different too and the largest share is taken by communication faults **F1** (16.4 %). The areas of concern are the affiliation points between the mechanical complexes, equipment packages or the automation systems. As new teams are introduced to the project, the documentation and information exchange becomes more important and is an area of faults. A substantial group of discovered faults is negligence **F2** (14.9 %) and mistakes made during installation, calibration and configuration of field instruments. **F3** type of faults in the commissioning stage (13.4 %) can be described as a designer's inability to consider systematically the production processes. In some cases, omitted procedures **F3** can indicate the omissions during HAZOP and SIL assessment.

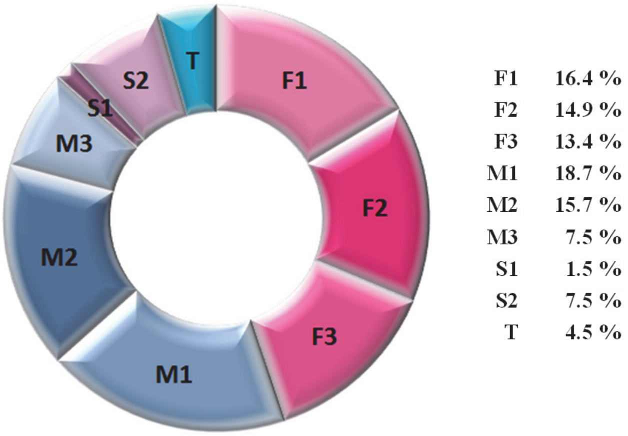


Figure 2.5. Statistics of shortcomings of the design of process automation system discovered during the commissioning of the factory. See the classification scheme in Fig. 2.3.

The second and a smaller part of the discovered shortcomings are mistakes **M.** The largest share is lack of competence **M1** (18.7 %). As the systems and subsystems commonly used are complicated, deep knowledge and experience is increasingly important and overall process knowledge proves insufficient. A usual shortcoming is lack of experience in integrating different types of process equipment mechanically and logically and experiencing the synergy of joint operation. Sometimes the systems delivered to the factory by different suppliers are in different levels of development and their functionality with other systems is not tested carefully enough. Also, behaviour of equipment combined into the process system can differ from designed properties, causing modifications in initial information packages. In this case, problems are classified as **M2** (15.7 %), an impossibility of predicting the variables. This category is increasing in today's conditions of rapidly advancing technology. Problems of compatibility form a majority of mistakes **M3** (7.5 %), systems integration disability.

Strategic miscalculations group **S** (9 %) is slightly smaller than during the FAT, but it is still important to address the category, as the resources and time possibly involved are relatively large. Because of the financial pressure, the installation and commissioning contractors try to take a package as large as possible to survive in a dynamically changing market. But their knowledge and experience may not be enough for the fast-developing field of process automation. The pace of development leads to insufficient training and lack of latest know-how.

Technical shortcomings **T** (4.5 %) in the commissioning phase are mainly caused by the damage of transportation or handling, unsuitability of equipment or faulty communication interfaces between the subsystems.

The nature of shortcomings in the commissioning phase is different from that found during FAT, but the human and teamwork related problems still dominate.

The summary statistics of human shortcomings of the design and commissioning of the automation control system from the database contains data of 26 factories. The distribution of shortcomings is quite close for a majority of the projects. In summary, to remove the difficulties during the project covering all teams in the project, on average between 1500 and 3000 working hours of additional working time are required. Additional losses result from a later start of production and non-completion of contractual obligations towards customers. Finally, the influence of human shortcomings on the effectiveness of the project depends highly on the competence of the project teams, but also on the complexity of the task. As any of the shortcomings may be leading to chaotic behaviour of the socio-technical system, it is extremely important to keep the whole process under control.

2.4 Conclusions of Chapter 2

1. A unique empirical database of human shortcomings observed at industrial process control system project design and commissioning was composed. This information collected during 15 years consists of real data about 26 projects. The database helps verify the efforts to confine the losses due to the "bad" engineering in the industrial control system design and commissioning.

2. The usability of the collected empirical data as an input for further research needs a classification of optimally detailed shortcomings. Therefore, an updated classification was composed where changes in the human action environment, i.e. developments in technology and business, are taken into account. As the share of newly introduced classification items is clearly essential, a broader classification area has proved to be a step in the right direction.

3. The data about human shortcomings were collected separately for the automation system design and its commissioning. It was found by the analysis of the collected data that the data for the design and the commissioning phase of the project differ to such a degree that it is impossible to sum them. During the design phase, the faults clearly dominate but during the commissioning, the share of mistakes reaches close to equality. It is necessary to point out that each type of human shortcomings needs a different approach for tracking and hindering the reasons of faulty behaviour.

4. Commissioning the industrial control system project consists of several test procedures, being the final blocking zone for human shortcomings. High demands to the reliability and availability of an automation system make the commissioning period extremely intensive and additional shortcomings due to the time pressure may arise.

3. EMPOWERING THE PREVENTIVE CHAOS CONTROL IN HIERARCHICAL MULTI-AGENT TEAMWORK

3.1 Outline of the theoretical research plan

Since 1998, the author of the thesis has been involved in about 30 industrial control system projects in more than 20 countries. All of these projects have suffered from difficulties caused by an expanding chaos due to the dissemination of human shortcomings. It always leads to additional expenses and sometimes to the problems to keep to an agreed time-schedule. To solve this problem, it is reasonable to address the synergy-based approach that considers communication as a cornerstone for minimising the losses of time and finances caused by rework and delays.

This thesis research focuses on the synergy-based chaos control in a complex hierarchical teamwork similar to the realization of the industrial process control system project. The studies are a logical follow-up to the previous research group activities and are based on the collected experience about the functioning of hierarchical multi-agent systems during the industrial process control systems design and commissioning. The main problem here is a reality that human shortcomings spread through multi-agent information channels can give rise to a chaotic behaviour of the agents participating in the design and commissioning process. Major efforts and finances are necessary to avoid a catastrophe as a factory's inability for production. To improve the situation, it is necessary to create an effective chaos control system for well-timed blocking and hindering the spreading of human shortcomings in this multi-agent system.

Current research plan can be described in two levels, which may be specified as a preventive and an active level. The first level activity is determined to avoid chaos genesis and dissemination during the design and commissioning of an industrial control system project. It requires a new approach to improve teamwork effectiveness through empowering the cooperation synergy level. First, it is inevitable to outline the detailed overview of all information flows and cooperation tasks in the project with a proposal of weights of collaboration intensity on the project description level. It has been proved by experience that the most suitable tool for the description and analysis of the complex multi-agent system is the use of the DSM matrix technology (Eppinger, 1997). For the present analysis, an overall information transfer documenting system is required to follow up the critical areas of chaotic dissemination of human shortcomings. As a result, effective procedures can be created to hinder and stop the propagation of human shortcomings in the multi-agent system. The only real way to predict human shortcomings is the statistical evaluation of their occurrence probability on the basis of empirical research (see Chapter 2). In this nonlinear world, the mapping of shortcoming trajectories is the only possible process description tool. To understand the reasons of chaos, it is necessary to identify the source of chaos and map possible trajectories of human shortcomings spreading in the hierarchical teamwork system. Based on a deep analysis, it is necessary to propose a suitable strategy to discover the human shortcomings earlier than with traditional scheduled approach and to hinder chaotic behaviour in the teamwork system.

Second level activities for fighting the chaos include forming temporary meta-structures for smooth project execution and building up the online system of continuous tracking and appropriate reaction to human-related faults and mistakes during the automation project execution. Here it is necessary to focus on the transfer on timing the project execution. First, the statistically estimated duration of the project execution is based on the time distribution and communication pattern. According to the noticed deviations of statistics during the project execution, the inputs of modelling must be respectively modified to find an optimal layout of the teams forming, communication profiles and workload distribution. It is required to develop an inhibitive chaos control system for mapping the areas of shortcoming forming and well-timed dynamic correction of the synergy level for introducing corrective perturbances like reasonable rework and tune-in for disposing the trajectories of shortcomings and preventing chaotic behaviour. The main difficulty here is that all human shortcomings are casual by nature. Thus, the linear mathematical tools appear to be useless and only a set of soft computational modelling tools are beneficial.

Next, dynamics of the use of the concept of synergy in the present research is addressed. The essence and story of effective use of the synergy concept and was described in section 1.4. The synergy exploitation to the solution of engineering design task problems has been studied by the TUT research group already during 20 years. Experience of the research group in the deployment of the synergy was acquired on product engineering design and manufacturing, where the workforce is comparatively stable and limited in the framework of one enterprise. In the present thesis, the synergistic approach has to be applied to a larger hierarchical socio-technical teamwork system.

In the context of the present thesis, the quantitative evaluation of synergy moves to the first plan. For this, it is appropriate to use the percentage scale (Fig. 3.1), where 0 represents a synergy-free system. 100 % means reaching maximum synergy, when everything is squeezed out of the communication and cooperation processes. Negative synergy -100 % marks the catastrophe situation where the whole process has failed and further activities are stopped. However, it is difficult to evaluate the exact value of existing synergy as its maximum level cannot be determined. The level of synergy must be maximal for the space and nuclear technology, somewhat lower for military space technology and is fully dependant on market demands for ordinary products such as factory process control systems. In principle, the synergy can be measured also by the rework time put into the empowering of the synergy.

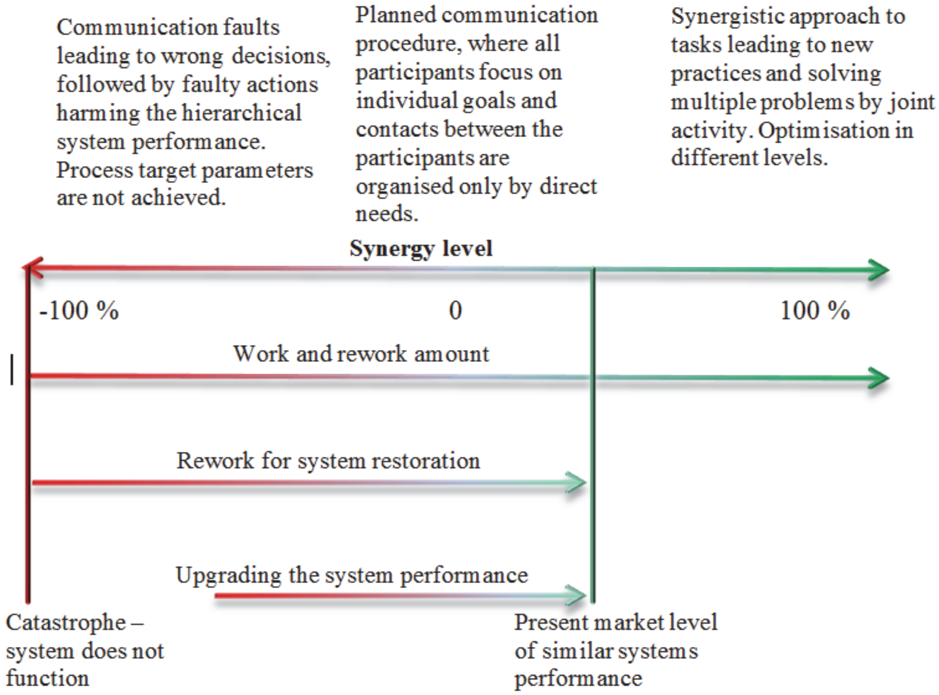


Figure 3.1. Positive and negative synergy relation to the work amount.

To empower the synergy in teamwork, it is substantial to focus on the quality of cooperation during solving common tasks and also quality of information transfer. Full comprehension of the human faults and mistakes spreading in the hierarchical teamwork and causing the chaos in the automation system design and commissioning is the most valuable information here. The only way to improve the situation is to empower the synergy in teamwork by means of compensation of mutual weaknesses and amplification of useful effects.

3.2. Disposition of cooperation in the hierarchical teamwork

To analyse any process, it is necessary to have a full description of all the inputs, agents, their activities and interfaces between them during the whole designed process time as a fundamental basis. The research team has used the DSM tool in the analysis of the multi-agent systems for a long time. In section 1.3, the different DSM types are presented. In this study of the dynamic hierarchical teamwork system, clustering of people and teams in an organization is the most suitable type of DSM (Eppinger and Browning, 2012).

Organisation architecture consists of three mappings: hierarchical decomposition, work assignments and information flow. The first two are represented in the organisation chart (Fig. 3.2), the third can be applied to the DSM matrix (Cho, 2001). The modelling of project teams enables us to form the most suitable metateams based on communication between the teams members and scheduling personal activities during the design and commissioning of a typical industrial process automation project. An organisation's structure can be designed in different ways based on the experience and understanding of necessary actions and communications. The rational organisation design includes also such applications of integrative mechanisms as co-location, meetings, communication technology, trainings, management, process modelling, etc. (Galbraith, 1994; Eppinger and Browning, 2012).

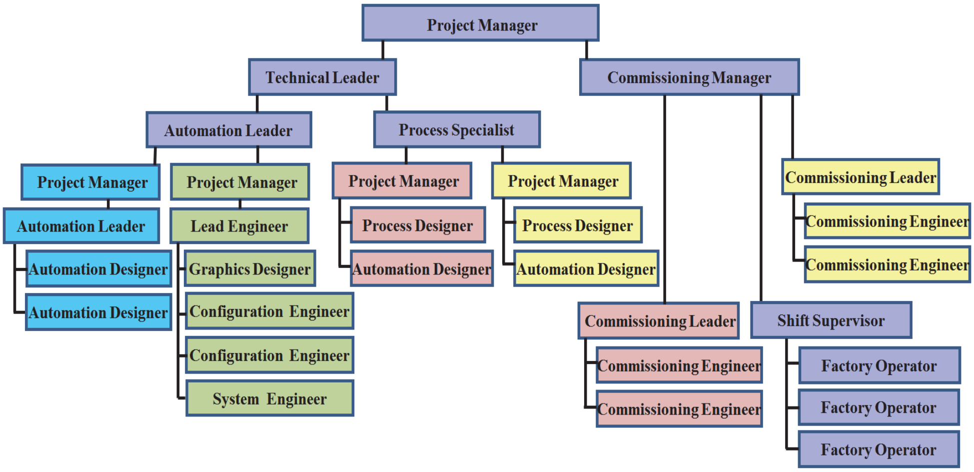


Figure 3.2. Organisation chart of a traditional industrial process automation team.

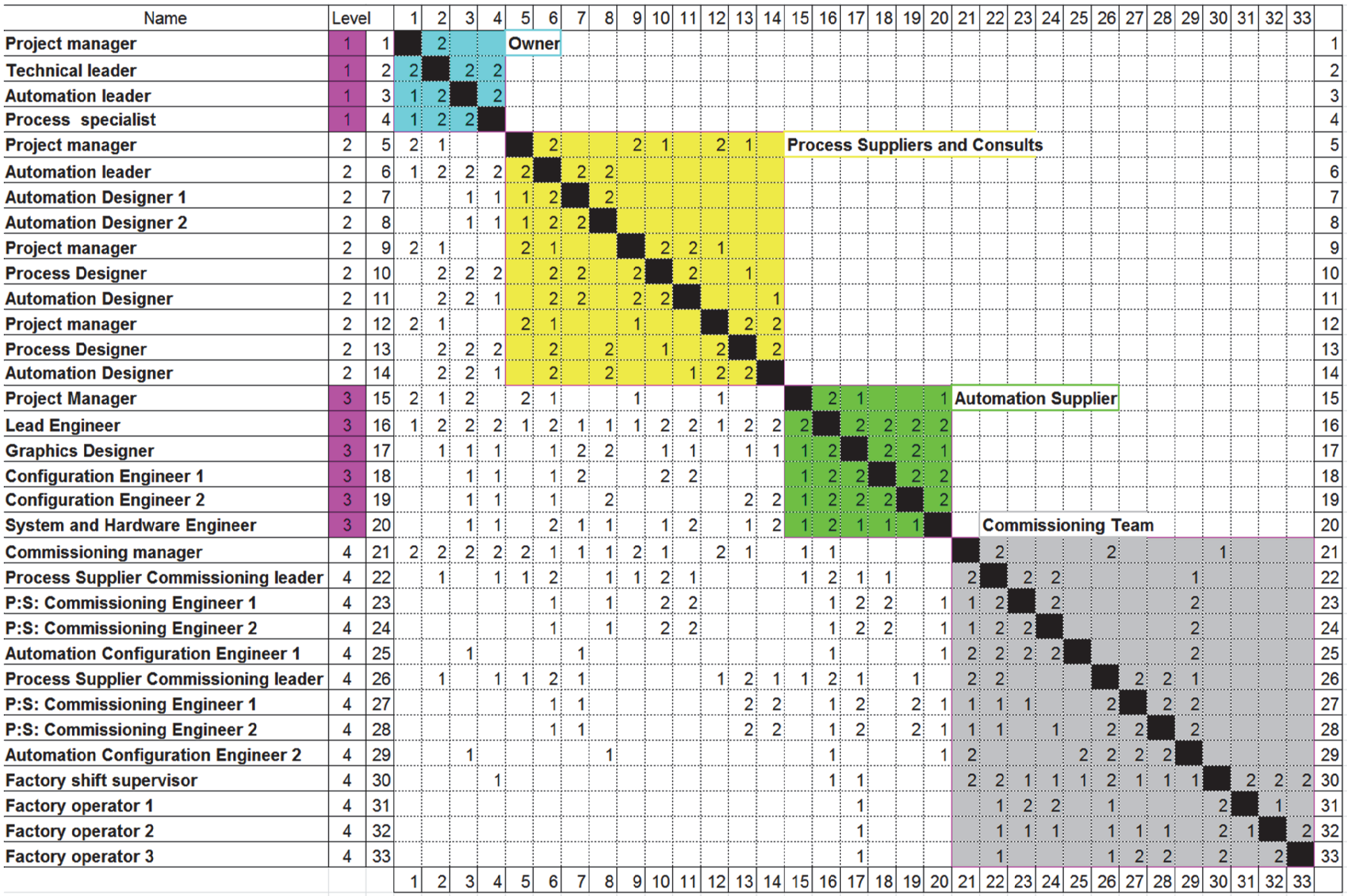
Traditional approach to a temporary hierarchical project organisation is based on the teams formed by commercial sub-projects and binding of the actions together by an owner's responsible team activities. A rational deterministic project team structure is presented in Fig. 3.3, where the teams for certain sub-projects are marked with different colours that represent different companies involved in the project organisation. Effective execution of project tasks by the team members requires planning of information flows between the team members and the different companies involved. But at the same time there is a risk of information overload, where an unreasonable amount of time is used to find necessary information among huge loads of data and attending to the non-essential meetings. The quality of information decreases as attentiveness dissipates due to information overflow. Also, there is a risk of information loss due to e-mail overflow, where the successfulness of communication may not be verified. Thus, information flow during the project execution has to be managed and controlled carefully.

Automation project team structure can be enhanced using the restructuring possibilities of the DSM matrix. The communication data are introduced to the matrix compiled by project team members in a sequential order. The number of team members is practically unlimited, but in the current research, the project team in an average project is formed by about 30 team members. The communication and co-operation strength (synergy) presented in the matrix is characterised on three levels: low or random (0, blank), moderate (1) and strong (2) (see Fig. 3.3). The direction of communication is very important and is readable in the matrix. If the information flow direction is from top down, the communication is marked to a sub-diagonal part of the matrix. Super-diagonal part of the DSM matrix is filled if the information from the team member positioned below in the matrix is needed to complete the task of the team member positioned above. The scope of information introduced to the matrix plays an important role in growing the synergy in teamwork.

Filling the data into the DSM input matrix forces the project team to analyse real communication needs and their frequency, providing also awareness of real communication needs to the project manager and their reality. Additionally, the matrix provides an overview of the whole project and reveals possible shortcomings of critical competence and helps to discover areas uncovered in the communication pattern. At the same time, the experience and competence of the whole team is introduced to the system, giving the dimension of adaptability to the system. The DSM method enables us to visualise the communication map and use further DSM mathematical treatment to optimise the composition of the working group and cluster most capable metateams (Fig. 3.4) where the communication is more vigorous. The coloured rectangles represent a new metateams suggested by the DSM tools. The black boxes indicate the traditional, contract-based team’s structure.

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

Figure 3.3. The raw communication data in the DSM matrix form.



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

Figure 3.4. Communication matrix data after using the DSM mathematical tools of clustering.

The further modelling of the matrix allows scheduling of the activities and predicting the time required for completing certain tasks considering probable iterations and rework (Eppinger, 2001; Kaljas, 2005; Hindreus, 2009). The mathematical processing of the DSM matrix indicates that it is unreasonable to handle consulting and process design teams separately but it is useful to integrate them into one metateam where the communication is smoother and direct, not considering the contractual boundaries of different companies involved. Similar behaviour is expected for commissioning engineers and factory employees. They need to be treated as group members irrespective of organisational and financial aspects. In addition to metateam's internal communication, there is a certain amount of external communication with other teams presented. Communication between metateams can be handled by appointing appropriate liaisons with suitable skills and expertise to organise information exchange between the metateams.

The chaotic behaviour of the hierarchical teamwork system can be substantially reduced with the help of the DSM technology. Mathematical tools reveal the problems in the communication structure and decompose working groups into cross-functional teams. The information transfer is a base for planning the application of integrative mechanisms in the project, including communication planning, regular meeting scheduling, planning workplaces and co-locating metateams, compiling e-mail distribution lists, appointing liaisons, etc. Manipulation of DSM communication patterns enables us to create alternative layouts of organisational structure and to find an optimal one for project success. However, the DSM matrix is static and does not consider the time factor. The time can be introduced to the analysis by using soft computing tools and discrete event modelling.

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

3.3 Growth of hierarchic chaos in the system

Communication in the project hierarchical teamwork system is usually organised according to the work assignments and decisions to be done inside the project. The scheduling of teamwork is supervised by the project manager and team leaders. However, substantial direct communication between the team members is also occurring, but the schedule is somewhat random and uncontrolled. The initiator of information exchange is usually the team member who needs certain input to perform a specific task. These task performing schedules are normally managed by project leaders but the final communication pattern is dependent on the team member's qualification, personalities, historical and cultural profiles, geographical locations, working habits, motivation, etc. Many responsibilities given to the team members involve general tasks when the progress feedback is requested in a certain period. A traditional communication pattern in an example project organisation is visualised in Fig. 3.5.

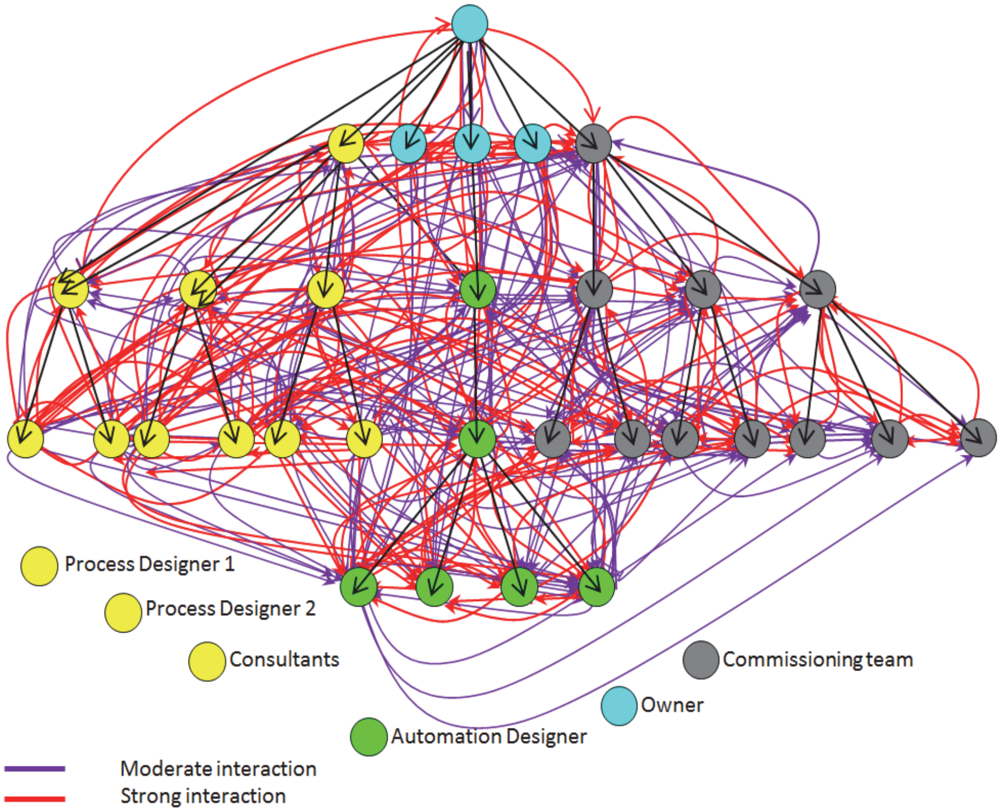


Figure 3.5. Graphical representation of hierarchy and communication in the automation project, reality scheme based on Fig. 3.3.

The scheme in Fig. 3.5 is a traditional hierarchical structure of the project teams created on the basis of companies and contracts. Small teams are supervised through the project by an owner's team. Communication between the teams members is represented by arrows of two colours, where violet marks moderate interaction and red accordingly strong communication and cooperation. The direction of the arrow represents the initiator of communication, i.e. one person passing over the information to another or requesting an explanation. Communication can be also bidirectional in mutual discussions and meetings.

A multi-agent hierarchical teamwork system is very sensitive to tainted and imperfect information transfer. The agent's decision or action is dependent on the decision made by another agent with an upper position in the information flow. The transfer of imperfect information leads to poor decisions that consequently lead to an exponential increase of chaotic behaviour, downgrading the performance of the whole teamwork system. Such a "butterfly effect" where small causes can have large effects may result in a real chaos in the industrial control system project, making the whole system extremely complicated and nonlinear. In the case of poor decisions, the trajectory of an actual process starts to differ from that predicted and the amount of shortcomings in a particular subsystem is increasing, pushing the process trajectory towards catastrophe (Fig. 3.6).

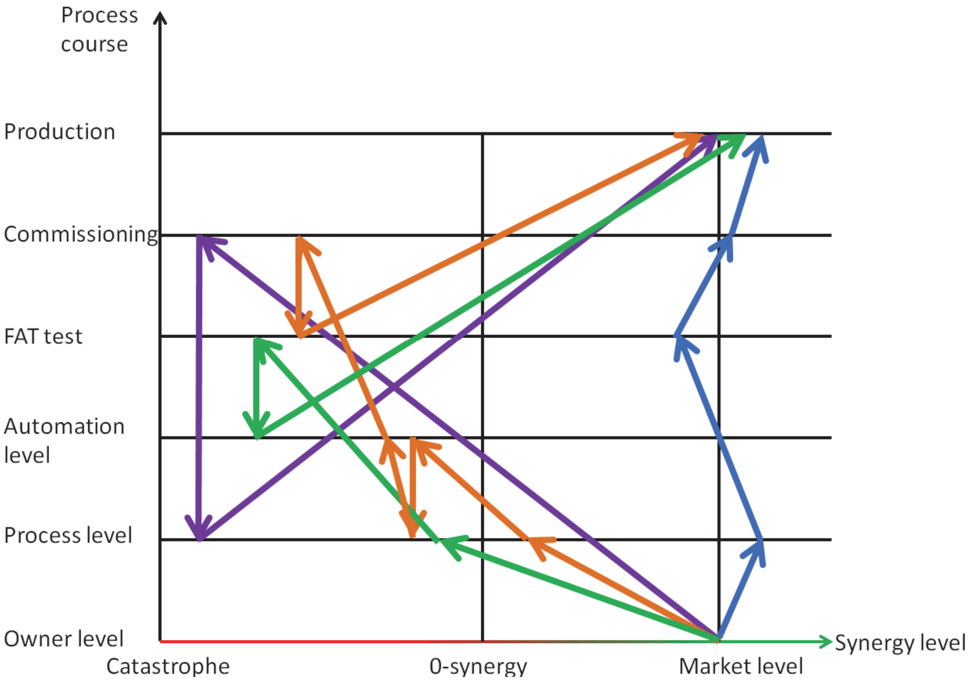


Figure 3.6. Example trajectories of shortcomings.

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

Depending on the project phase where the destructive movement in the system is discovered, the problematic path can be taken back in the process to the point where the first wrong decision was made and the process starts from here again with building up the correct trajectory. Alternatively, also some weighted perturbance can be introduced to the system, pushing the trajectory towards that desired. Perturbance can be an additional pattern in the communication matrix, redistributing the timing inside the project and involving an expert to the working group who will organise additional training or some other action to avoid further distribution of shortcomings.

It is essential to add time and synergy dimensions into the existing scheme. All the efforts to move the result of the process towards a market level on the synergy scale need some additional cooperation exertion, leading to empowering the synergy of process in a precondition that the most appropriate strategy is chosen with a reasonable supervision of the result.

3.4 Strategy of tracking, hindering and blocking the human shortcomings dissemination

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

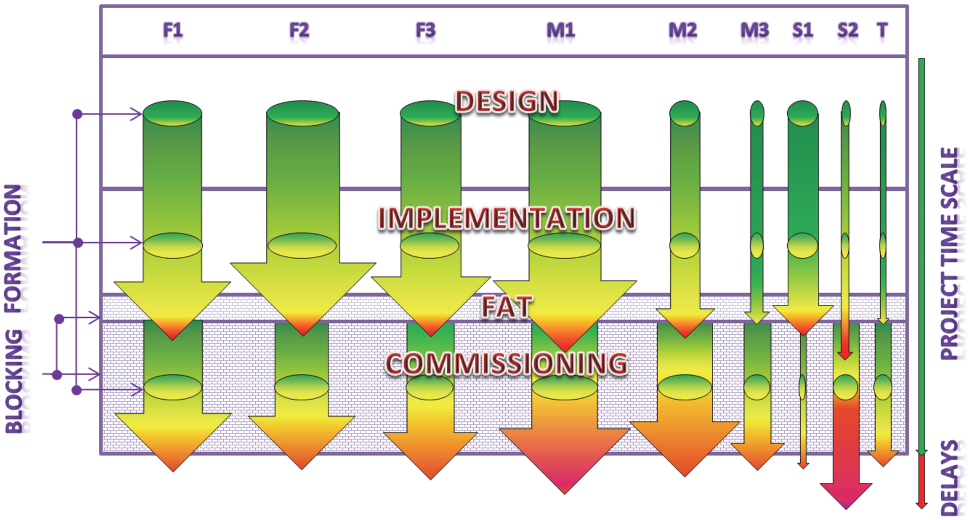


Figure 3.7. Impact of shortcomings on the whole project time.

Figure 3.7 visualised the spreading of shortcomings in the time scale of project execution. The formation zones of shortcomings are shown as those integrated, considering the fact that origination of the human fault or mistake may happen at any moment on the time-scale. FAT and commissioning are shown here as blocking zones of shortcomings where the deviations are discovered. Horizontal dimensions of the arrows represent the statistical share of the shortcomings of each type discovered during the FAT test and commissioning, respectively. The length of the arrow of shortcomings present the real working hours spent on the correction of the impact of a specific shortcoming calculated from an average project and based on the real shortcomings database. The overrun of the longer arrows on the time-scale shows the delay of the project start-up in the sample project. In real life, the delay is conditional, as it depends on the availability of human resources with necessary competence that can be concentrated at the elimination of the impact of certain types of shortcomings. The duration of the sample project is considered to be one year.

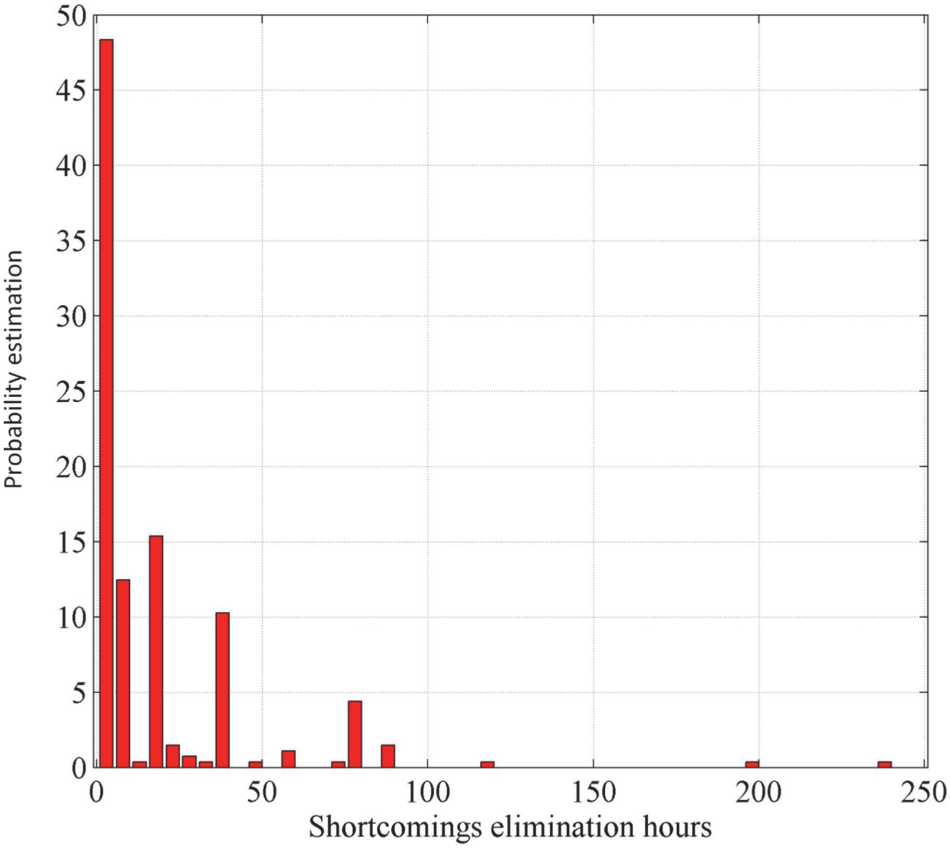


Figure 3.8. Probabilistic prediction of the time for removal of the results of shortcomings.

From the results of the analysis of the shortcomings database, an anticipated probabilistic prediction of the time needed to eliminate the shortcomings was found during the design and commissioning of the process automation system (see Fig. 3.8). The vertical axis shows the percentage of probability to run into the shortcoming, where rework of a certain amount of hours is required (horizontal axis). From the shortcomings distribution graph it is obvious that the probability of small problems is considerably higher than the time-consuming ones. However, the impact of small problems cannot be underestimated, as even simple mistakes can start the receding of the process trajectory from an ideal one and be a source of chaos growth in the system. Thus, it is inevitable to introduce also probabilistic share of detailed faults and mistakes into the perspective schemes from the empirical studies of human shortcomings to consider their impact on the behaviour of the dynamical hierarchical teamwork system.

Scheduling the project time has presumably a probabilistic nature that can be analysed only by help of soft computing tools. It is a complicated task considering the fact that modified or new or corrected information is appearing occasionally during project execution, causing iterations and rework. Today the shortcomings are mainly revealed in two blocking zones of the project (see Fig. 3.7) because communication procedures are overlooked during the project design phase. The amount of repetitive work is decreasing in the course of time mainly according to the learning curve based on the similarities of shortcomings. According to the probabilistic analysis of occurrence of shortcomings, it is possible to engage preventive measures to hinder the start of chaotic behaviour. To react to problems more efficiently, it is essential to create a dynamic probabilistic tracking system on the basis of statistical evaluation that helps to discover the growth of chaotic behaviour, focusing on the critical areas in the communication pattern. The critical areas of communication, where the probability of the formation of shortcomings is highest, can be identified by applying the shortcomings data from the empirical database in the team structure matrix. Additional smaller blocking zones need to be created for prompt reaction to the appearance of shortcomings. Further discrete event modelling brings the time factor into the analysis process, allowing finding the best communication matrix and an optimal team structure to minimise the time for rework and iterations during project execution.

At the same time, the process of the industrial control system design and commissioning needs to be evaluated continuously from a synergetic point of view to introduce appropriate perturbances into the teamwork system for inducing possible chaotic trajectories to follow a preferable trajectory. Together with enhanced communication map and task-oriented distribution of workload, it enables us to prevent the rise of chaotic behaviour in the system, to reduce rework and accordingly to reduce the whole project duration.

3.5 Conclusions of Chapter 3

1. Deployment of the effects of synergy raises problem of its quantitative evaluation. As synergy cannot exist in a linear world, it is most suitable to use a percentage scale. In the teamwork context, synergy increase is measurable by the rework done for enhancing the system performance quality.

2. To handle project work as a complete system, it is necessary to integrate the hierarchical decomposition, work assignments and information flows to one package. Besides an easy survey of the described system, the possibility of its mathematical treatment is indispensable. It was shown that the Design Structure Matrix (DSM) technology is suitable tool for teamwork integration, which allows forming task-oriented metateams and scheduling communication in a dynamical teamwork.

3. Chaotic dissemination of human shortcomings can cause unpredicted nonlinear trajectories of rework during project execution due to the tainted and imperfect information transfer. To minimise rework, it is essential to react in time to minor deflections from the predicted shortcoming trajectory and introduce perturbances to diminish possible proliferation of chaos.

4. A carefully deliberated communication pattern is a basis for forming optimal metateams for a smooth project execution in the conditions of preventive hindering of human shortcomings dissemination. During project execution, it is required to evaluate the pattern continuously and modify it based on the peculiarities of the team's synergistic performance.

5. The traditional system of verification of the automation project performance is insufficient. Measures to shorten the project execution duration by enhancing the communication pattern, task-oriented distribution of workload and dynamical tracking of project execution are necessary.

4. METHODOLOGY FOR TIMING THE PROJECT EXECUTION

4.1. Prognosis of the project execution time

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

In principle, there are two ways of planning the project duration – a deterministic and a probabilistic approach. Earned value management (EVM) methodology is one of the most straightforward and common deterministic methodologies for project monitoring (Willems and Vanhoucke, 2015). The result of this technique is point estimate when the project is planned to end to a certain date. Probabilistic approach has a larger degree of variations and the result includes distributions and confidence intervals around the estimates (Willems and Vanhoucke, 2015). Due to the complexity of the present task and the fact that deterministic methods cannot handle the dynamical structure of the teamwork in the conditions of accidental human shortcomings, the only way is prognosis of project duration by probabilistic modelling. It is a very complicated task to model, as at iterations the modified information may arrive at any moment of the process of rework. It is natural that the amount of repetitive work is reducing during the project execution according to the learning curve.

A suitable modelling technique for the system performance evaluation seems to be computing the duration using parallel discrete event simulation (Pritsker and O'Reilly, 1999; Zeigler et al., 2000; Cho, 2001). In this model, the events are triggering the transitions and time progresses in discrete steps between the events. Parallel simulation enables more than one component to be active at the same time and send the outputs to other components. The Latin Hypercube Sampling method is more suitable for calculating the expected durations, including possible iterations, in the technical systems (Cho and Eppinger, 2001). An event is defined here as a cooperation or communication activity. The model initialises the variables, adjusts the durations of the tasks and generates the sequential iteration rework using a probabilistic rule and computing probability distributions for the expected durations. The expected duration of an agent's time allocation is based on the probabilistic experience-based prediction. However, there is some spare time reserved for handling the shortcomings. The model takes into account the working hours available for resource, rework probability, learning curve, and team composition. The probable project duration computation model using the tools of DSM and Latin Hypercube Sampling is presented in Fig. 4.1.

The inputs for the system performance evaluation model are as follows:

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

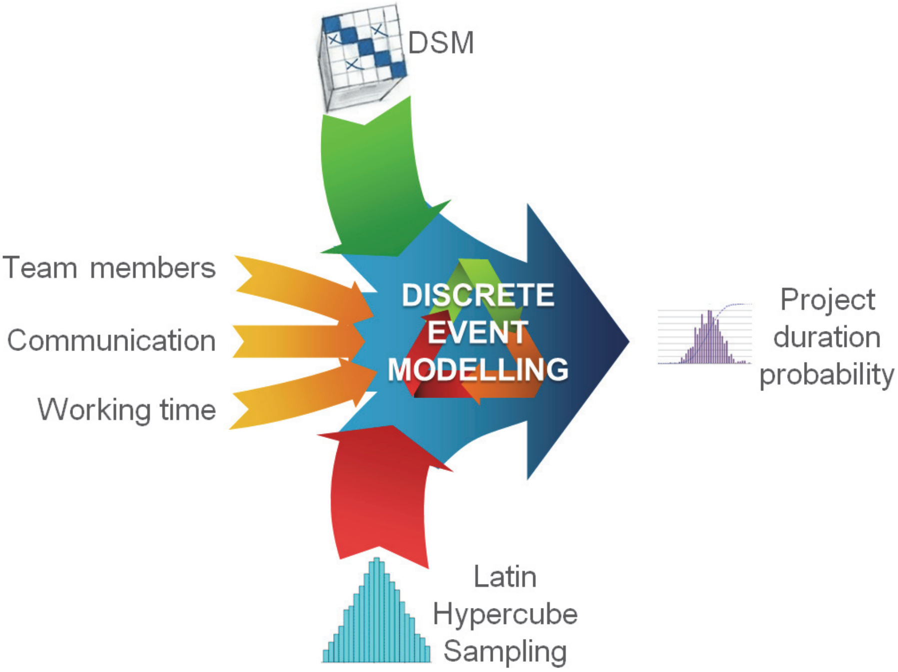


Figure 4.1. Modelling of probable duration of a project.

First, the project duration is calculated with a traditional approach for execution of the industrial control system design and commissioning where the teams are based on companies and contracts and communication is scheduled considering an optimistic scenario of fully successful communication. The tasks are planned as sequential and parallel, provided that the team below in the matrix (Figure 3.4) starts the work after information package from the team above is handed over. For testing the proposed methodology, the average project duration was used for discrete event modelling, based on the experience of the author. Total working hours for this example project were calculated to be 12 000 h (100%) and the duration of the project was considered to be one year. To present more clear results, the duration was transferred to % scale.

The output of discrete event modelling is the chart of sampling results enhanced with the cumulative probability curve (Fig. 4.2), where the probable project duration can be seen.

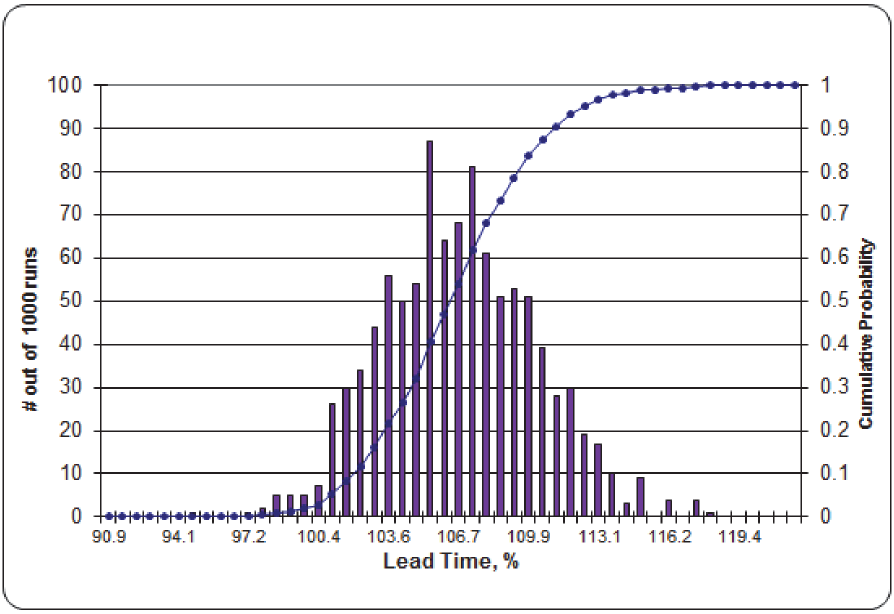


Figure 4.2. Possible duration of the project as a discrete event modelling result.

The nominal duration (Fig. 4.2) of 100 % is expected to be by the conditional schedule, overlooking human shortcomings and their chaotic dissemination. However, taking into account the human shortcomings data (section 2.3), the real duration of the project schedule is exceeded by 6.5 % with a cumulative probability of 0.5. As it can be seen in Fig. 4.2, there is a very slight possibility to finish the project in schedule if the corrective actions for tracking and hindering the shortcomings are not implemented and communication schedule not considered and updated.

The value of the proposed methodology is in the addition of the real dispersion area to the traditional project execution time, caused by inevitable human shortcomings and estimated on the basis of their statistics. In traditional project management, these losses are not taken into account. From this basis, it is possible to start development of a new approach targeted to reducing the project duration. The first instrument here is communication pattern upgrade that results in an intentional metateams structure change.

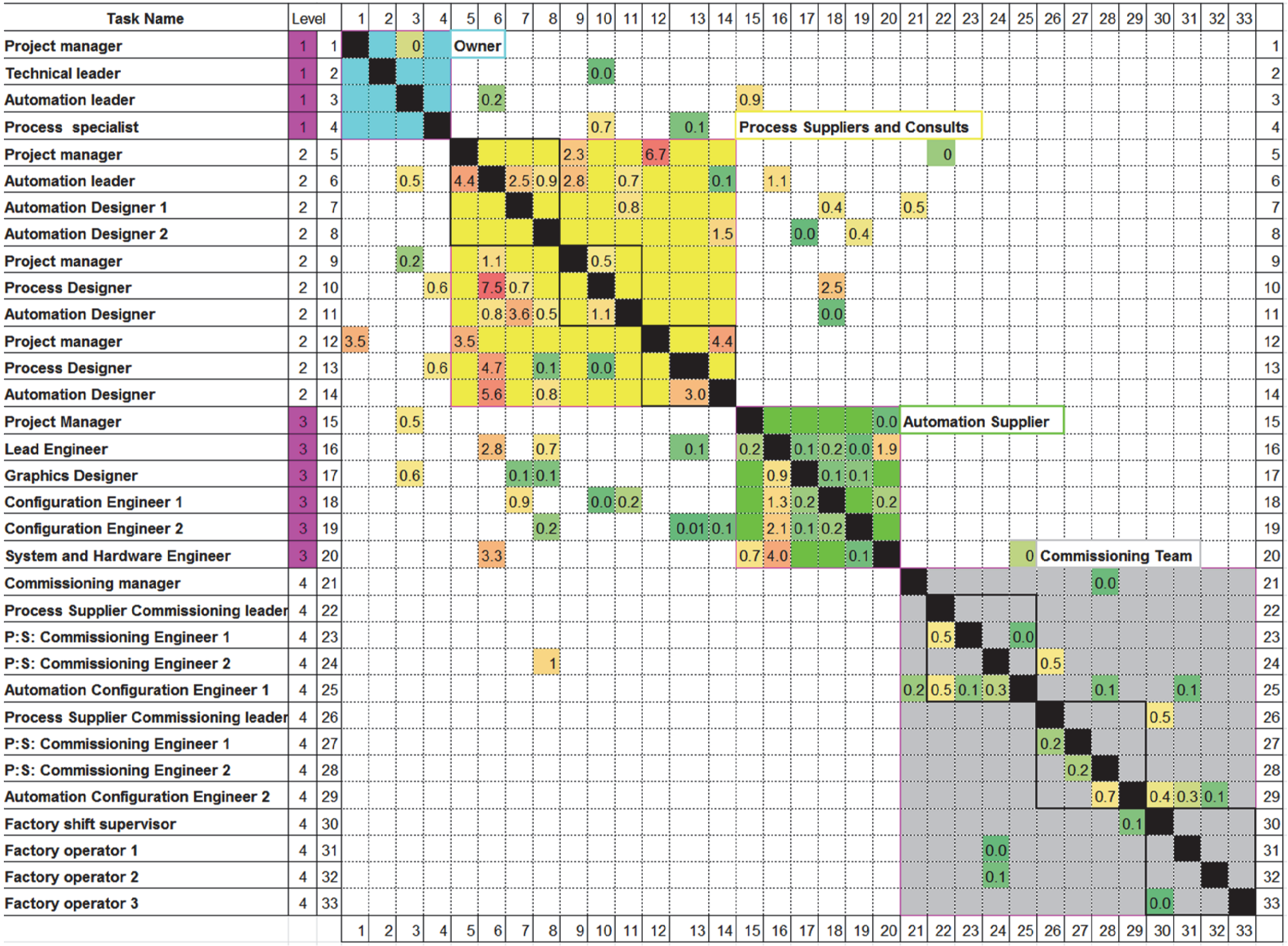
4.2 Upgrading the project communication

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

Further analysis of the human shortcomings database considering origination of the problems in the communication network and the time needed to eliminate them in the shortcoming blocking zones is visualised in Figure 4.3. From the database, the impact of the shortcomings on the rework hours was transformed into a percentage scale and efforts needed to finalise the project were introduced to the clustered matrix form. The percent weight of the shortcomings was marked to the cell where the communication problem arose.

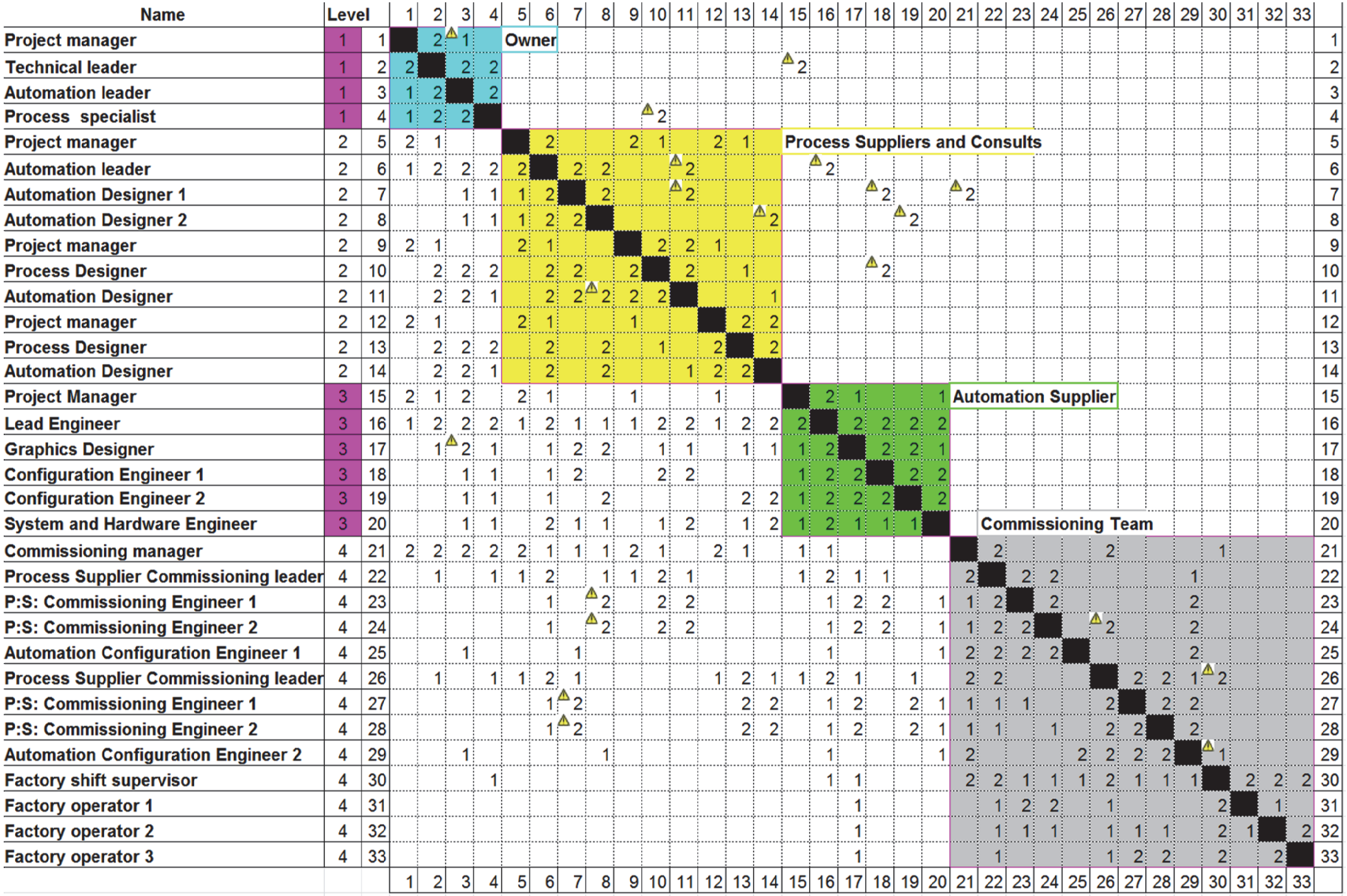
The analysis shows that a majority of the problems falls to the area of clustered metateams (blue, yellow, green and grey areas), indicating a need for reforming to reduce the communication insufficiency. Most common company-based team structure is shown with black bordered rectangles. The idea of dynamical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

As it was explained in Chapter 3, the communication map is compiled in a 3-level scale, where 0 (blank) represents random non-planned communication, 1 stands for moderate, and 2 for strong scheduled face-to-face communication and tight cooperation in daily work. Some of the sources of chaotic shortcomings cannot be considered on the scheduled communication map, so the matrix needs continuous upgrading by adding and modifying the communication rules. At scheduling a new communication map for metateams, the problematic areas in the matrix need to be improved by mapping additional communication points into the patterns or increasing the strength of existing ones (Fig. 4.4, marked with⚠). Also, if no communication problems have occurred in a specific area, it might be reasonable to lower the communication level. However, changes in the cooperation profile need to be handled case-by-case without corrupting existing successful communication network.



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

Figure 4.3. Map of shortcomings in the DSM matrix form.



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

Figure 4.4. Upgraded communication matrix.

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

Proposed metateams' forming methodology is inevitable to support the optimization regarding the reduction of the project execution time. Traditionally, similar solutions are made on the basis of intuition, but human brain is able to work out only simple solutions. In more complicated situations, it is possible to optimise reactions on growing chaos only through multiple metateams formation and to verify their optimality by discrete event modelling.

4.3 Reducing project duration by empowering the synergy

To reduce the influence of human shortcomings and faulty communication on the teamwork system, it is necessary to introduce the synergy-based activities to raise the quality of teamwork. Resulting from the evaluation of a metateam's structure and enhanced communication matrix it is obvious that it is required to reschedule the workload of the participating team members on basis of empirical data of human shortcomings. DSM-based mapping of the communication structure increases the comprehension of interactions so that right information can be made available at the right place and at the right time (Browning, 1999). Additionally, the impact of delays in information transfer can be identified by tracking the information flows. Such improvement efforts as changing the communication pattern, allocating additional resources, overlapping the tasks introduced to the model are reducing the risk of delays in the teamwork system (Cho, 2001).

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

In the present case, the experience-based data are introduced to the dynamical model to find out an optimal additional time distribution based on data about shortcomings and their causal analysis. There may be different experience-based setups of data for modelling, used at allocating additional time to team members based on the empirical data of human shortcomings and their removal time (see Table 4.1). The critical problem for every project leader is how to divide the rework time at necessary iterations in the project work. According to the assumption based on long-term experience in automation projects, the probability of wrong decisions is decreasing by 40 % when the possible source of shortcomings has 20 % more time for completing the task. In the same way, it is possible to state that 40 % of additional time lowers the probability of poor decisions by 55 % and 60 % of time contribution leads to reduction of shortcomings probability by 70 %. The percentage of additional time is calculated from the time spent for rework to eliminate the impacts of human shortcomings. This philosophy is helpful for looking the possibilities of exploiting the chaos control principle to achieve remarkable effects by applying small disturbances. This effect is also well known in synergetics at the border of transfer to the area of self-regulation (Haken, 2004). But this assumption must be approved by modelling. With a decreasing probability of chaotic behaviour in the teamwork, the rework probability is smaller, thus releasing some time from the agents that are normally dealing with hindering the chaos dissemination.

Table 4.1. Data setups for additional time allocation.

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

Discrete event modelling of probabilistic duration of the project (Figure 4.5) shows that the use of data set 1 is an optimal solution, where 20 % of time spent for rework is distributed between the team members that were responsible for making wrong decisions that started the chaotic behaviour in teamwork. The probabilistic duration of the project is shorter than using another setup for additional time distribution (see Table 4.1). Figure 4.6 shows the time distribution graph where the original values stand for the allocated working time from a traditional project schedule and the modified graph represents the time distribution after modifying time allocation based on the empirical research of human shortcomings. The changes in the time allocation are relatively small, but are giving significant results on shortening the project duration.

For final modelling, all the proposed assumptions were applied: enhanced metateam's structure with agile project handling methods allowing more parallel operations instead of sequential, improved communication pattern considering empirical results of the shortcomings database and continuous tracking of occurrence of shortcomings to minimise the chaos dissemination.

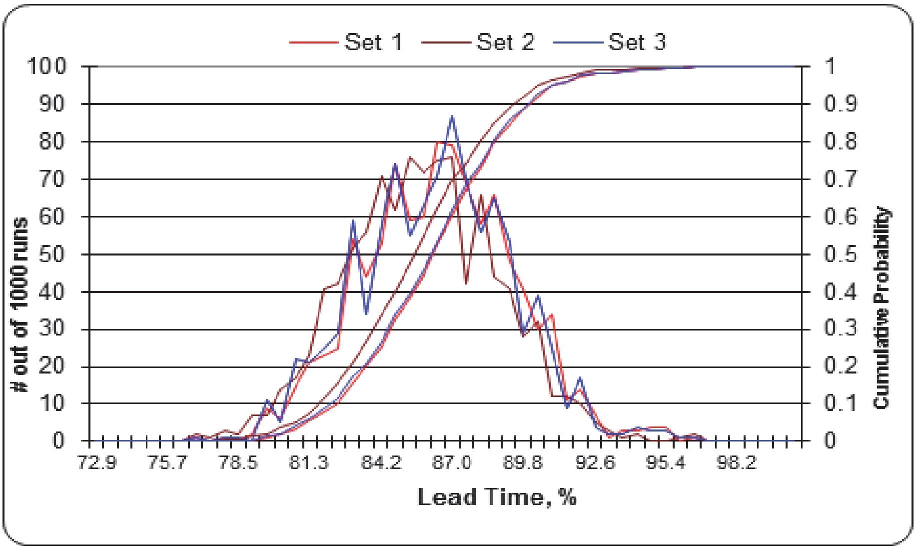


Figure 4.5. Modelling results with different time distribution.

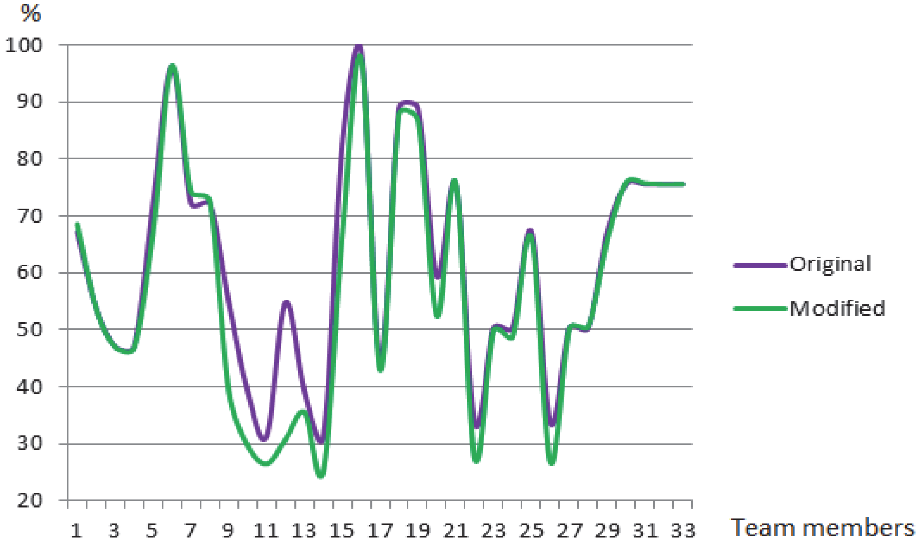


Figure 4.6. Modifications in the time distribution between the team members (see also page 69).

On the basis of the probabilistic analysis of the “bad” engineering cases of project team members during the project, the tracking maps of human shortcomings must be compiled, enabling evaluation of the probabilistic impact of the different types of shortcomings (see Fig. 3.6). These maps are completed by integrating the synergy-based approach to communication activities. To reduce the shortcoming arrival, it is necessary to grant optimal time for careful completion of the tasks both for the teams and individuals inside the teams, where the source of chaotic behaviour is higher. In compliance with the quality of information transferred to the next levels growing, a subsequent agent does not need as much time for evaluating the transferred information and the risk of possible rework is decreasing.

Automation system often becomes the critical part of start-up the production as it is the final element to be implemented. All the process equipment needs to be installed and working before the control system can be finally commissioned and tuned. Thus, the parallel activities for rework become extremely important to minimise the delays causing problems with the realization of revenues of an industrial plant due to late start-up.

In summary, the presented methodology of discrete event modelling enables computing probability distribution of a task’s execution time in the project matrix where iterations and rework take place in sequential and parallel tasks. Results of the analysis enable the evaluation of the time losses due to the faults and mistakes in the information network considering necessary iterations, reworks and learning curves.

Now it is appropriate to evaluate the impact of all proposed methodologies - clustered metateams approach, tracking of shortcoming arise and working time distribution based on predictions from the shortcomings database - for the realization of a real industrial automation project. The discrete event modelling results reveal significant shortening of project execution time, from 106.5 % (Fig. 4.2) to 85.4 % (Fig. 4.7) with the cumulative probability of 0.5. This gives confidence about not exceeding the planned start-up date and refers to significant savings on the labour cost. It is necessary to underline here that these are theoretical limits for capable competent teams. Inexperienced teams under incompetent management of the project may cause an increase of time losses prognosis.

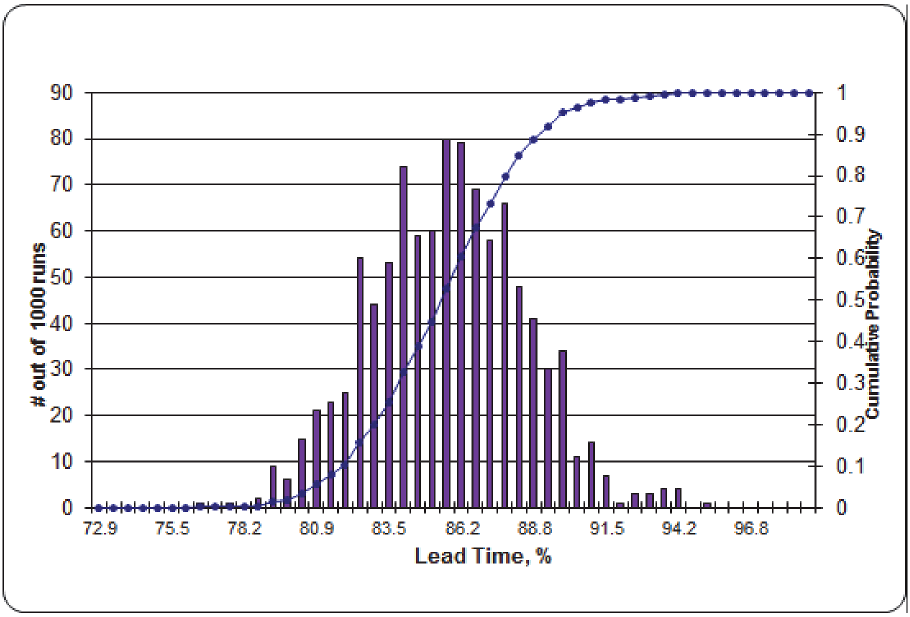


Figure 4.7. Possible duration of the project after using proposed methodologies.

For an average project used as an example in the current thesis, the modelling resulted with 6.7 % of savings in direct labour costs (Table 4.2) and 21 % of shortening the project duration (Fig. 4.8). Thus, the proposed approach to upgrade the project management enables remarkable savings.

Table 4.2. Labour costs during project execution.

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

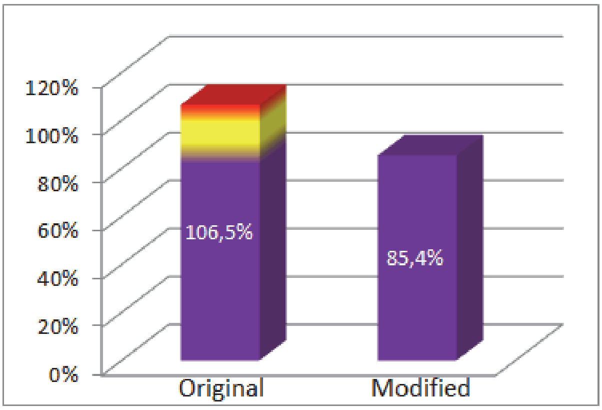


Figure 4.8. Comparison of average project duration.

The conventional approach to project management leading to average project duration of 106.5 % (Figure 4.8), where 6.5 % of the delays are due to human shortcomings are marked red and 14.6 % that can be reduced by synergetic approach to teamwork system dynamics are marked yellow in the graph.

The methodology for growing the synergy level in hierarchical teamwork system by handling human shortcomings arise and chaotic dissemination is successfully verified and proved to be beneficial. The probabilistic prognosis of the project duration shows reduction of project overall duration by 21 % and direct labour costs reduction by 6.7 % with cumulative probability of 0.5.

4.4. Conclusions of Chapter 4

1. An advanced methodology of prognosis of the duration of the industrial automation design and commissioning project is proposed. An additional value of this methodology is the prediction of the dispersion range due to an inevitable action of human shortcomings during the execution of the project. The dispersion range is counted by discrete event modelling. The use of this methodology is fully authentic, as it is based on the database of the empirical study of human shortcomings in multiple similar projects.

2. As the arrival of human shortcomings is fully accidental, a reliable mathematical tool is needed to deal with hindering dissemination of the human shortcomings. It is proved that the best possible tool for this purpose is the Discrete Event Modelling technology. This allows integration of the DSM technology with the metateams communication map, agents' activity parameters and enriching it with the Latin Hypercube Sampling, resulting in the chart of probabilistic duration as an outcome.

3. A methodology of reducing the project duration is proposed. This methodology is supported by the use of a smart shortcoming tracking and hindering system with the temporary metateams to eliminate the consequences of shortcomings dissemination. During the project execution, the occurrence of shortcomings is continuously tracked and probabilistic chaotic trajectories and their possible quantitative impact is analysed for prompt reaction of communication schedule upgrade, possible modification in metateam's structure or working time distribution between the team members and remodelling of probabilistic duration of the project.

4. A technology for forming smart action metateams is proposed based on upgrading the Design Structure Matrix (DSM) technology. The core of this approach is based on the introduction of the statistics of the human shortcomings into the matrix with further mathematical treatment of the matrix to find the best metateams solution.

5. The results of the thesis research were verified. Modelling the average project duration shows that an average probabilistic project duration is 106.5 % of the predicted project time with a cumulative probability of 0.5, i.e. there is a high possibility for delays of 6.5 % or even more of the project nominal duration. Majority of these delays are caused by the human shortcomings improperly handled. The proposed methodology enables a 21 % reduction of the duration of the project execution, allowing to start the automation part of the project later in the overall time schedule and enabling remarkable savings in labour costs and timely start-up of production.

CONCLUSIONS

1. The empirical knowledge and experience database of human shortcomings observed in the hierarchical teamwork of the automation project design and commissioning was compiled by the author of the thesis, drawing together data from 26 industrial control system projects. Taking into account the developments in the technology and business, an advanced classification of human shortcomings for this database was developed to allow the causal evaluation of shortcomings for further research.
2. The industrial process automation project as an interactive hierarchical social process of communication and decision-making is strongly affected by chaotic dissemination of human shortcomings. Imperfect or tainted information transfer calls forth a specific form of hierarchical chaos with singular chaos spreading trajectories in the teamwork system. To handle this phenomenon, a specific two-level chaos control system was developed, consisting of a preventive and an operative level.
3. For the preventive chaos control, the Design Structure Matrix (DSM) technology is proposed as the most suitable tool for the design of the communication management and introducing preventive measures to block human shortcomings dissemination and to treat the whole system mathematically. On the basis of DSM, an original approach to form the dynamical temporary metateams structure is proposed for fast reaction to human shortcomings disclosure. The core of this approach is the introduction of the statistics of the human shortcomings into the matrix, with further mathematical treatment of the matrix to find the best metateam solution.
4. For the operative chaos control due to the accidental nature of human shortcomings, the discrete event modeling technology enhanced with instruments of DSM and Latin Hypercube Sampling was found to be a suitable tool for modelling of the present nonlinear dynamical structure. Upgrading of the communication pattern, task-oriented distribution of workload, dynamical tracking of project execution and forming of the temporary metateams compose the foundation for the proposed methodology for reducing the prognosis of project duration.
5. The testing of the methodology of proactive chaos control by temporary chaos mapping and well-timed dynamic empowering of the synergy level by reasonable rework and tune-in has shown that it is possible to reduce the project target time and corresponding labour costs remarkably. It is proved that the most powerful effect on the blocking of human shortcomings is achieved by increasing synergistic information transfer procedures between all project teams and their members.
6. A methodology of mapping the shortcomings dissemination on the project evolution plane was developed. These maps are the strategic basis of synergy deployment in chaos control, allowing eliminating chaos by moving with

applied disturbances the trajectories towards market level performance of the system by empowering the synergy effects.
7. An advanced methodology of prognosis of the duration of the industrial automation design and commissioning project is proposed, based on discrete event modelling. An additional value of this methodology is the prediction of the dispersion range due to an inevitable action of human shortcomings during the execution of the project. The use of this methodology is fully authentic, as it is based on the database of the empirical study of human shortcomings in multiple similar projects.
8. The chaos control in the hierarchical socio-technical systems was bound into teamwork management by describing the trajectories of shortcomings. It provides the scientific background to the evaluation of the shortcomings dissemination in the system and enables using perturbances to move the shortcomings trajectories close to those desired.
9. Verification of the research results by modelling the project duration shows that by applying the proposed solutions at human shortcomings initiated chaos control, the direct labour costs during the hierarchical project execution can be reduced by 6.7 % and the total project duration can be suppressed by 21 %.

The **novelties** to be highlighted in the present research are as follows:

A unique database of human shortcomings has been collected by the author during 15 years, drawing together data about 26 industrial plants control system design and commissioning process experience.

A temporary metateam forming methodology is proposed for hierarchical chaos control based on upgrading the Design Structure Matrix (DSM) technology. The core of this approach is the introduction of the statistics of the human shortcomings into the matrix with further mathematical treatment of the matrix to find the best metateam solution.

An advanced methodology of prognosis of the duration of the industrial automation design and commissioning project is proposed. An additional value of this methodology is the prediction of the dispersion range due to an inevitable action of human shortcomings during the execution of the project.

In the **future research**, it would be reasonable to follow two sequential steps. First, it is important to develop suitable software that would bind the results of the current research into one package usable by project managers as an additional tool for empowering synergistic approach to teamwork planning and tracking. As a second step, it is recommended to integrate the mentioned software with the existing project management software. For easier use, it is helpful to develop suitable data-transfer scenarios utilising existing information in the project management software and handle the whole project using one universal software tool.

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KOKKUVÕTE

Sünergiapõhine kaose juhtimine paljuagentsetes hierarhilistes süsteemides

Käesoleva doktoritöö eesmärgiks on uurida sünergiapõhise lähenemise võimalusi tõstmaks multiagentse hierarhilise meeskonna töö kvaliteeti tingimustes, kus seda paratamatult mõjutavad inimlikud vead ja eksimused. Uurimisobjektiks on tööstusliku automaatjuhtimissüsteemi projekteerimise ja käivitamise protsess. Töö tulemusena on vaja saavutada inimressursside optimaalne kasutusmudel, et vältida inimfaktorist põhjustatud ajakadusid tehaste käikulaskmisel.

Käesoleva doktoritöö hüpoteesid on järgmised:

1. Hierarhilises paljuagentses süsteemis esinevad inimpõhised vead põhjustavad kaootilisi ilminguid, mõjutades hierarhias allpool olevate agentide otsuseid ning viies sellega kogu süsteemi tasakaalust välja.
2. Kasvava kaose vältimiseks on mõistlik kasutada struktuurmaatriksite tehnoloogiat (DSM), mis võimaldab meeskonnatöö optimeerida, moodustades tööülesannetel põhinevaid metameeskondi ja restruktureerides kommunikatsiooni dünaamilises ajutises meeskonnatöös.
3. Projekti kestuse prognoosimiseks on võimalik luua metoodika, kasutades selleks diskreetsete sündmuste modelleerimist, mille aluseks on inimpõhiste vigade ja eksimuste andmebaas.
4. Kasutades kaose ennetavat juhtimist, selle trajektooride kaardistamist ning täpselt ajastatud meetmeid, on otstarbeka kordustöö ja seadistamise abil võimalik tõsta sünergia taset süsteemis. Sellega saavutatakse oluline kokkuhoid projekti kestuses ja maksumuses.

Et püstitatud eesmärgini jõuda, tuleb uurimistöö raames lahendada järgmised probleemid:

1. Läbi viia empiiriline uuring inimlike vigade ja eksimuste mõjust tööstusliku automaatjuhtimissüsteemi projekteerimis- ja käikulaskmisprotsessile.
2. Hinnata kaose juhtimise meetodite rakendatavust paljuagentsete hierarhiliste meeskondade töös ja pakkuda välja strateegia inimlike vigade ja eksimuste jälgimiseks, hindamiseks ja tõkestamiseks.
3. Luua metoodiline raamistik projekti kestuse määramiseks, lähtudes statistilisest inimpõhiste vigade ja eksimuste andmebaasist ning leida võimalused projekti aja ja materiaalsete vahendite kokkuhoiuks kaootiliste seisundite ilmnemisel.

Doktoritöö esimeses osas on läbi viidud põhjalik teaduskirjanduse uuring töös käsitletavate probleemide hetkeseisust tänapäeva teadus- ja tööstusmaailmas. Peamiste valdkondadena on uuritud automatiseerimistehnoloogiaid ja nende arengusuundi, paljuagentsete hierarhiliste organisatsioonide toimimist, sünergia rakendamist meeskonnatöös, süsteemide kvaliteedi tagamise probleeme jne. Uuringu fookuses on automaatjuhtimissüsteemide projekteerimine ja käikulaskmine kui käesoleva väitekirja uurimiskeskkond. Keskne teadusprobleem on kaose tekke jälgimine ja tõkestamine paljuagentsetes hierarhilistes süsteemides, nagu seda on automaatjuhtimissüsteemide projekteerimine ja käivitamine. Eriline tähelepanu on pühendatud sünergia taseme tõstmisele, mis läbib siduva faktorina kogu uurimistööd. Olulise osa uurimusest moodustab sobivate matemaatiliste töövahendite otsimine, mis võimaldaksid püstitatud ülesandeid lahendada.

Doktoritöö teises osas on kirjeldatud unikaalse statistilise andmebaasi koostamist, mis põhineb reaalsete suurte automaatikasüsteemide projekteerimisel ja käikulaskmisel ilmnenud inimlike vigade ja eksimuste analüüsil. Väitekirja autor on osalenud erinevatel ametipositsioonidel enam kui kolmekümnes tööstusprojektis automaatjuhtimissüsteemi projekteerimis- ja käivitusmeeskondades erinevates maailmajagudes ning rohkem kui kahekümnes riigis. On võetud kasutusele uus ja põhjalikum inimpõhiste probleemide klassifitseerimise skeem, mis võimaldab vigu ja eksimusi eristada lähenedes nende lahendamisele sõltuvalt probleemi tekke iseloomust . Andmebaas ja selle analüüs moodustab reaalse aluse uurimistöö väljundite saavutamiseks ja hindamiseks.

Kolmandas osas on käsitletud empiirilise uurimuse sidumist kaose juhtimise problemaatikaga, kusjuures uuritakse inimpõhiste probleemide levikut hierarhilises süsteemis leidmaks võimalusi nende jälgimiseks, trajektooride kaardistamiseks ning tõkestamiseks. Kaootilise käitumise leviku tõkestamine sõltub otseselt selle kaardistamise efektiivsusest ja täpsusest.

Neljas osa on pühendatud tööstusautomaatika projektide kestuse prognoosimise metoodika väljatöötamisele, mis võtab arvesse inimpõhiste eksimuste statistikat. Eesmärgiks on välja pakkuda juhiste kogum projekti kestuse lühendamiseks ja leida paindlikud võimalused töö käigus tekkivate muudatuste sisseviimiseks.

Uurimistöö tulemusena on jõutud järgmiste järeldusteni:

1. On koostatud unikaalne inimlike vigade ja eksimuste empiiriline andmebaas, mis haarab ajavahemikku 1999 – 2014 ja sisaldab teavet 26 tehase automaatjuhtimissüsteemi projekteerimise ja käivituse kohta. Uus inimpõhiste vigade detailne klassifitseerimismeetod, mis on loodud, arvestades tehnoloogia ja majandustegevuse arenguid ja võimaldab kasutada empiirilisi andmeid inimpõhiste vigade põhjuslikuks analüüsiks.

2. Tööstusautomaatika projekt kui interaktiivne hierarhiline sotsiaalne kommunikatsiooni- ja otsustamisprotsess on tugevalt mõjutatud inimtekkeliste vigade ja eksimuste kaootilisest levikust. Ebatäpse või vigase informatsiooni levik põhjustab spetsiifilise hierarhilise kaose vormi tekke koos üksikute kaootiliselt levivate trajektooridega meeskonnatöö süsteemis. Selle käsitlemiseks on välja arendatud spetsiifiline kahetasandiline kaose juhtimise süsteem: ennetav ja operatiivne.

3. Ennetaval tasandil kaose juhtimiseks on soovitatud struktuurmaatriksite (DSM) tehnoloogiat kui kõige sobivamat kommunikatsiooni juhtimiseks ja ennetavate meetmete rakendamiseks inimtekkeliste probleemide leviku tõkestamisel ning kogu süsteemi matemaatilisel käsitlemisel. DSM abil on loodud originaalne lahendus dünaamiliste ajutiste metameeskondade moodustamiseks, mis inimpõhistele vigadele ja eksimustele operatiivselt reageerida suudavad. Selle metoodika tuum peitub inimpõhiste vigade ja eksimuste statistika rakendamises DSM matemaatilisel töötlemisel leidmaks parim võimalik metameeskondade struktuur.

4. Kaose juhtimise operatiivsel tasemel, arvestades inimtekkeliste probleemide juhuslikku loomust, on ainuke sobiv meetod mittelineaarsete dünaamiliste struktuuride käitumise uurimiseks diskreetsete sündmuste modelleerimine, mida täiendavad DSM tehnoloogia ja ladina hüperkuupide meetod. Kommunikatsioonimustri täiendamine, tööülesannetel põhinev töökoormuse jagamine, projekti kulu dünaamiline monitoorimine ja ajutiste metameeskondade moodustamine loovad tugeva põhja loodud metoodikale vähendamaks projekti kestuse prognoosi.

5. Proaktiivse kaose juhtimise metodoloogia katsetamise käigus, kasutades jooksvat kaose kaardistamist ja ajastatud dünaamilise koostöö sünergia taseme tõstmist põhjendatud taastegemise ja ümberhäälestuste abil on tõestatud, et sel teel on võimalik tunduvalt vähendada projekti sihtkestust ja tööjõu maksumust. On tõestatud, et kõige tugevam mõju inimpõhiste vigade ja eksimuste blokeerimisel on saavutatav sünergiapõhise informatsiooni edastamise protseduuri rakendamisel nii meeskondade kui ka selle liikmete töös.

6. Välja on töötatud projekti käigus tekkivate inimpõhiste eksimuste leviku kaardistamise metoodika. Need kaardid moodustavad strateegilise aluse sünergia kasvatamiseks kaose tingimustes, võimaldades kaootilisi ilminguid elimineerida suunates kaootilisi trajektoore väliste mõjurite abil soovitud suunas, et saavutada turul nõutav süsteemi töövõimekuse tase läbi sünergia suurendamise.

7. Toetudes diskreetsete sündmuste modelleerimisele on välja töötatud uuenduslik metoodika tööstusautomaatikaprojektide projekteerimise ja

käikulaskmise kestuse prognoosimiseks. Selle lisaväärtuseks on töö hajuvuse prognoos, arvestades vältimatut inimpõhiste probleemide teket projektitöö jooksul.

8. Kaose juhtimine hierarhilises sotsiotehnilises süsteemis on seotud meeskonnatöö juhtimise ning eksimuste trajektooride kirjeldamisega. See annab eksimuste leviku hindamisele teadusliku tausta ning võimaldab rakendada mõjureid suunamaks eksimuste trajektoorid soovitud suunas. Sünergiapõhine lähenemine projekti meeskonnatööle, koostööle ja kommunikatsioonile on keerukate tööstusprojektide jaoks uus suund, mille vajadust on tõestanud selle positiivne mõju projekti prognoositavale ajagraafikule ja eelarvele

9. Testides töö tulemusi modelleerides projekti prognoositavat kestust, on jõutud järelduseni, et pakutud metoodikat rakendades inimtekkeliste probleemide põhjustatud kaose käsitlemiseks on võimalik otseseid tööjõukulusid vähendada 6,7 % ja kogu projekti kestust kuni 21 %.

Käesoleva doktoriitöö uudsuse seisukohalt võiks välja tuua järgmised aspektid:

1. Autor on 15 aasta jooksul kogunud põhjaliku unikaalse inimpõhiste eksimuste andmebaasi, mis sisaldab reaalseid andmeid 26 tehase automaatjuhtimissüsteemi projekteerimise ja käivitamise projekti kohta. Uus inimpõhiste vigade detailne klassifitseerimismeetod võimaldab ennustada probleemseid trajektoore hierarhilises süsteemis. Andmebaasi on kasutatud projekti kestuse tõenäosuslikuks prognoosiks.
2. Ajutiste metameeskondade moodustamise metoodika on loodud kaose juhtimiseks hierarhilistes süsteemides, mis põhineb struktuurimaatriksite (DSM) tehnoloogial. Selle metoodika sisu peitub inimpõhiste vigade ja eksimuste statistika rakendamises DSM matemaatilisel käsitlemisel leidmaks parim võimalik metameeskondade struktuur.
3. Universaalne metoodika on välja arendatud projekti kestuse käsitlemiseks läbi meeskonnatöö modelleerimise. Selle lisaväärtuseks on töö hajuvuse prognoos arvestades vältimatut inimpõhiste probleemide teket projektitöö jooksul.

Kaose juhtimine hierarhilises sotsiotehnilises süsteemis on seotud meeskonnatöö juhtimise problemaatikaga ning eksimuste trajektooride kirjeldamisega. See annab eksimuste leviku hindamisele teadusliku tausta ning võimaldab rakendada mõjureid suunamaks eksimuste trajektoorid soovitud suunas. Sünergiapõhine lähenemine projekti meeskonnatööle, koostööle ja kommunikatsioonile on keerukate tööstusprojektide jaoks uus suund, mille vajadust on tõestanud selle positiivne mõju projekti prognoositavale ajagraafikule ja eelarvele.

Töö tulemuste edasiviimiseks oleks mõistlik arendada metoodikaid edasi kahes järjestikuses etapis. Esmalt oleks vaja välja töötada sobiv tarkvara, mis seoks käesoleva doktoritöö metoodikad ühte tarkvarapaketti ja oleks projektijuhtidele hõlpsasti kasutatav lisavahend soodustamaks sünergia võimendamist meeskonnatöö planeerimisel ning jälgimisel. Järgmiseks sammuks oleks soovitav mainitud tarkvara integreerida mõne olemasoleva projektijuhtimistarkvaraga.

Märksõnad: tööstuslikud juhtsüsteemid, meeskonnatöö juhtimine, kaose juhtimine, sünergia rakendamine, projekteerimise struktuurimaatriks, diskreetsete sündmuste modelleerimine, projekti kestuse prognoosimine, projektijuhtimine.

ABSTRACT

Synergy-Based Chaos Control in the Multi-Agent Hierarchical Systems

The objective of the present doctoral thesis is to outline the synergy-based approach to empowering the performance quality of multi-agent hierarchical teamwork systems disordered by human shortcomings. The object of the research is the design and commissioning process of industrial automation systems.

The first part of the thesis reviews the literature covering research activities in the field of complex socio-technical systems optimization and specifies the key areas of the research. Current status of the development level of industrial control systems is analysed and peculiarities of teamwork and collective dynamics are described. The chaotic dynamics of binary systems and spatio-temporal chaotic dynamics were found to be useful environments to describe the process of the hierarchical teamwork system. Synergy-based optimization of teamwork and communication was found to be feasible to help attain the goals of the current thesis.

Chapter 2 of the thesis contains empirical research of human shortcomings in the industrial automation systems design and commissioning process. A unique empirical database of human shortcomings collected during 15 years contains comprehensive data about 26 industrial process control system projects. The classification of the human shortcomings database is optimally detailed to use the collected empirical data as input for further research, although each type of shortcomings needs a different approach to track and hinder the reasons of faulty behaviour.

Chapter 3 addresses the empowering of synergy in the hierarchical teamwork. The DSM method is used to form optimal metateams considering communication and cooperation needs from the synergistic point of view. Chaotic dissemination of human shortcomings is mapped to track the trajectories of shortcomings. It is essential to react to growing chaos to minimize the rework for bringing the system back to an acceptable synergy level. The definition of the quantitative percentage evaluation of the synergy level is given in relation to rework done for improving the system performance.

In the last part of the thesis, a methodological framework is developed using tools of the DSM technology with discrete event modelling and Latin Hypercube Sampling for timing the project execution based on upgraded communication and cooperation patterns. Capable metateams are formed and data about human shortcomings are applied for reducing the project time at their accidental arise. The task of cutting down the project duration using the synergy-based approach to teamwork problems was successfully completed and a methodology for this proposed.

Keywords: industrial control systems, teamwork management, chaos control, synergy deployment, design structure matrix, discrete event modelling, project duration prediction, project management.

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LIST OF PUBLICATIONS

Key publications related to present thesis:

1. **Källo, R.**, Reedik, V. and Eerme, M. (2016), Empowering synergy dynamics in chaos control in hierarchical teamwork. *Proceedings of the 11th International DAAAM Baltic Conference Industrial Engineering*. Tallinn, Estonia. https://www.etis.ee/Research/publications/Display/02660a20-01de-49c9-a7ef-1ba6ddcd66c7
2. **Källo, R.**, Reedik, V. and Eerme, M. (2015), On chaos control in hierarchical multi-agent systems. *Proceedings of the Estonian Academy of Sciences,* **64**, (1)*,* 17−21. http://www.eap.ee/public/proceedings_pdf/2015/issue_1/Proc-2015-1-17-21.pdf
3. **Källo, R.**, Reedik, V. and Eerme, M. (2014), Ways of increasing synergy in engineering design teamwork. *Proceedings of the 8th International Conference of DAAAM Baltic Industrial Engineering*. Vol. II. TUT Press, Tallinn, Estonia, 500−505. http://innomet.ttu.ee/daaam_publications/2012/k%C3%A4llo.pdf

Other publications devoted to thematics of the thesis:

4. **Källo, R.**, Reedik, V. and Eerme, M. (2014), On chaos control in hierarchical multi-agent systems, In: *Proceedings of The 9th International Conference of Daaam Baltic Industrial Engineering*. TUT Press, Tallinn, Estonia, 41−46. http://innomet.ttu.ee/daaam/proceedings/Design%20Engineering/K%C3%A4llo.pdf
5. **Källo, R.**, Reedik, V. and Eerme, M. (2013), Ways of increasing synergy in automated factory design and commissioning teamwork. *Journal of Materials Science and Engineering B*, 3 (9), 597−604. http://www.davidpublishing.com/davidpublishing/Upfile/3/2/2014/2014030274270057.pdf
6. Hindreus, T., Kaljas, F., **Källo, R.**, Martin, A., Tähemaa, T., Reedik, V. (2012), On synergy deployment in engineering design, *Journal of Materials Science and Engineering B,* 2 (6), 408−413. http://www.davidpublishing.com/davidpublishing/Upfile/7/16/2012/2012071606097190.pdf

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3. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (kraad/eriala)
Tallinna Tehnikaülikool	2004	Tehnikateaduste magister, Tootearendus
Tallinna Kõrgem Tehnikakool	1998	Masinaehitusinsener
Kiviõli 1. Keskkool	1994	Keskharidus

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

Keel	Tase
Eesti	kõrgtase
Inglise	kõrgtase
Vene	kesktase
Soome	kõrgtase

5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
1998-2016	Erinevad tööstusautomaatikat ja selle instrumente puudutavad koolitused Shveitsis, Hollandis, Soomes, Suurbritannias ja Eestis

6. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
09.2015 – tänaseni	Synarec OÜ	Juhataja/konsultant
06.2004-09.2015	HECC OÜ	Juhataja/konsultant
12.1998-05.2004	Filter AS	Projektiinsener

7. Teadustöö põhisuunad
Tootearendus
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CURRICULUM VITAE

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3. Education

Educational institution	Graduation year	Education (degree/field of study)
Tallinn University of Technology	2004	M.Sc. Mechanical Engineering
Tallinn Higher Technical School	1998	Mechanical Engineer
Kiviõli Secondary School No. 1	1994	Secondary education

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

Language	Level
Estonian	fluent
English	fluent
Russian	average
Finnish	fluent

5. Special Courses

Period	Educational or other organisation
1998-2016	Different automation and instrumentation related trainings in Switzerland, Finland, Netherlands, United Kingdom, and Estonia

6. Professional Employment

Period	Organisation	Position
09.2015 – up to present	Synarec OÜ	Manager/Consultant
06.2004-09.2015	HECC OÜ	Manager/Consultant
12.1998-05.2004	Filter AS	Project Engineer

7. Main areas of scientific work/Current research topics

Product development
Industrial control systems
Synergetics

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

1. **Jakob Kübarsepp**. Steel-Bonded Hardmetals. 1992.

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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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12. **Vitali Podgurski**. Laser Ablation and Thermal Evaporation of Thin Films and Structures. 2001.

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