THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Representing human-automation challenges
A model based approach for human factors engineering in industrial practice

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Abstract

Automation technology is widely implemented in process control domains due to its benefits of improving efficiency and enhancing control. However, use of automation also introduces an often complex intermediary between the human and the controlled domain, which can obscure from the operator how system functioning is achieved. The difficulty for operators to perceive and understand what the automatic system is doing has a potentially negative impact on overall system performance, since the human operator perform important functions in the work system related to both safety and production.

In this thesis it is argued that there are few approaches that address the problem of specifically, and each existing approach might individually not cover the entire problem scope in full detail. Further, current methodologies seem to have difficulties in reaching applications apart from narrow human factors engineering practices.

With this background in mind, the research work presented in this thesis has focused on how human-automation related challenges can be addressed to improve preconditions for operators in understanding automatic system functioning. Creating the appropriate preconditions in control environments is a multidisciplinary design challenge striving for safe and efficient work systems. The purpose of this thesis was to aid human factors engineering practitioners in industry in dealing with this challenge.

To fulfil the purpose, an existing theoretical model was adapted and used to describe human-automation challenges in general. This led to a theoretical unification of human-automation related challenges and a way to describe challenges systematically. The unified format enables description and analysis of automated human-machine systems in order to identify representational gaps and matches in the work system. The theoretical model was then used as a basis for developing a method named the “System Representation Matrix”. The System Representation Matrix enables description and analysis of the dynamic domain, the control system, the control system user interface and the necessary operator knowledge, in a unified representation.

Conclusions from testing and evaluating the method are that the System Representation Matrix can aid creating an overview of automated human-machine systems. The overview has potential as an aid for reasoning about matters of system functioning and design. In practice, the matrix could provide support for design decisions, help define necessary operator knowledge and become a tool to aid human factors engineering in multidisciplinary teams. This has the potential to lead to improved aid for human factors engineers when dealing with human-automation challenges in industrial practice.

Acknowledgement

First of all I would like to thank my main supervisor Professor Anna-Lisa Osvalder for giving me the opportunity to enter into the world of research. Your kind encouragement, support and guidance have been very helpful. Maybe sometime in the future I will learn to take care of my s's…

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I have to thank all operational personnel that have participated in my projects. You have endured endless questions, interviews, questionnaires, being observed and long and intentionally boring simulator sessions. Without you, there would have been no research worth mentioning.

My thanks too, to all practitioners who agreed to work with me on the projects. By sharing your experience and knowledge you made me a better researcher and a wiser man. And special thanks to those who helped me evaluate the developed method on such a short notice.

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The past few years prior to finishing my PhD have been the most challenging of my life in many ways. Writing a PhD thesis and being away from your loved ones could have been enough, one might think. At times, life is a maelstrom and we are but autumn leafs within it. Anywho… Tor, you kept me floating.

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Ulla, thank you for your love, care and sincere interest in my research work. We all miss you terribly.

Dad, you taught me to seek my own answers. It is the most precious gift I have ever received. Mum and Erika, without your endless support I would not be where I am now. Thank you for looking after me and my own little family.

Emilia, sing me one of your songs and I have peace of mind. It was the sweetest relaxation when my head was full of levels, matrices, boxes and lines.

Alfred, finally, FINALLLY the darn thesis is ready. Let’s play with LEGO!

To those of you who have read this far, I’m glad you managed. To those of you to have the intention to read further, I would like you to know that the effort put into this work would not have been possible without one person. Her name is Julia.

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Terms and definitions

There are several words that are used frequently in the thesis. To avoid misinterpretations a list of definitions of terms is shown in Table 1.

Table 1 Definitions

Term	Definition
Automation	'Automation' is defined as the **properties** of a technical system **to perceive, analyse, decide and/or act on its own** under different degrees of human involvement. The word automation is not used to describe the physical process equipment that possesses the property of automation. The term 'control system' is consequently used to denominate the physical system that enable automatic behaviour.
Automated human-machine system	An automated human-machine system is defined as a system where the technology in the system possesses one or more of the properties of automation (see above).
Complexity vs. complicated	Complexity within a technological system is often defined as the system having many parts and that the parts are highly interconnected (Stevenson, 2010). However, from the psychological view a technological system can be very complex yet understood by a person with the appropriate knowledge (Flach, 2012). The complicatedness of a complex system can thus be reduced by knowledge, e.g., appropriate conceptual models.
Conceptual model	A 'conceptual model' is defined as a construct of long term memory. A conceptual model contains knowledge of systems that informs reasoning and mental models. A conceptual model is static during task performance and resistant to change. It is non-task specific and informed by external representations (Richardson and Ball, 2009).
Control	'Control' is defined as the ability to direct the behaviour of a system 'Control' can be defined as a purposive influence toward a predetermined goal involving continuous comparison of current states to future goals (Skyttner, 2005)
Control system	The 'control system' is defined as the physical system that enables automation. Control systems possess the functions to perceive, analyse, decide and give orders to act.
Level of automation	Level of Automation is defined as 'the allocation of perceiving, analysing, deciding and acting between humans and technology, described as a continuum ranging between totally manual and totally automatic' (adapted from Frohm (2008))

Term	Definition
Mental model	A 'mental model' is defined as a short-term construct of working memory that is a means of reasoning about actions. A mental model is informed by conceptual models. A mental model is dynamic during task performance. It is task specific and informed by external representations (Richardson and Ball, 2009)
Model	A model is defined as an abstraction from reality that serves the purpose of ordering and simplifying our view of reality while still representing its essential characteristics (Grix, 2010).
System	A 'system' can be defined as 'a set or assemblage of things connected, associated, or interdependent, so as to form a complex unity' (Stevenson, 2010)
Work domain	The 'work domain' is 'the landscape within which the work takes place' (Rasmussen et al., 1994)
Work system	The 'work system' is defined as the unity of humans, technology and organisation in a context, involved in activity often trying to achieve a common goal. The work system is mostly a larger entity than the human-machine system.

1 Introduction

1.1 Background

The research in this thesis has mainly been performed in process control domains. Automation technology is widely implemented in process control domains due to its benefits of improving efficiency and enhancing control. However, use of advanced automation also brings increasing complexity into the work system. During normal operations the underlying complexity of automatic functions is a source of advantage, but in the case of adverse events the same complexity becomes a challenge to appropriate human interventions. Therefore, to avoid operational problems, human operators have to be given appropriate preconditions to understand the automation technology. In this research work I argue that the problems emerging when automation fails are not only due to the interaction between humans and the control system interface, but are also an issue concerning how different parts of the system represent each other. All system designers such as process engineers, control system engineers, user interface designers and operator educators and instructors play different roles in creating work systems that are productive and efficient, where the operator's role as a knowledge worker is key (Hollender, 2010). In this kind of multidisciplinary design context human factors engineering has an important contribution to make in incorporating human aspects into to the systems engineering design process.

One problem is that the transfer of human factors research knowledge from academia to industry is painstakingly slow. The reasons for the inertia of knowledge transfer are multifaceted and dependent on both organisational and individual factors (Berlin, 2011; Theberge and Neumann, 2010) The standpoint taken in my research work is however, that academics as method designers can help the knowledge transfer by developing methods that have high utility (i.e. provide results that are useful to practitioners in design) and are usable (i.e. adapted to practitioners' working context) in systems development (Andersson et al., 2011). In this respect there is a need for an approach capable of addressing specific human-automation challenges, and which at the same time is usable in an industrial development context. This doctoral thesis is an attempt to provide a viable tool to fulfil this approach.

1.1.1 Practical challenges in human factors engineering

In the research context of process control, human factors engineering to support human-control-system interaction faces multiple challenges that need to be met in order to integrate human factors engineering into an industrial development context in general, and for successful design interventions in particular. Figure 1 provides a simplified overview of the research context. The human factors practitioner has to gather an understanding of the context in which the design intervention will take place, e.g. have first-hand access to control room operators in authentic work situations. Work has to be studied and understood from a variety of situations that rarely occur, i.e. safety critical situations. Based on the understanding gained from the context, the human factors engineer has to draw conclusions and judge what type of theoretical knowledge is of importance in a particular case. And in this particular case, what kind of automation related challenges can be expected to occur given the contextual premises.

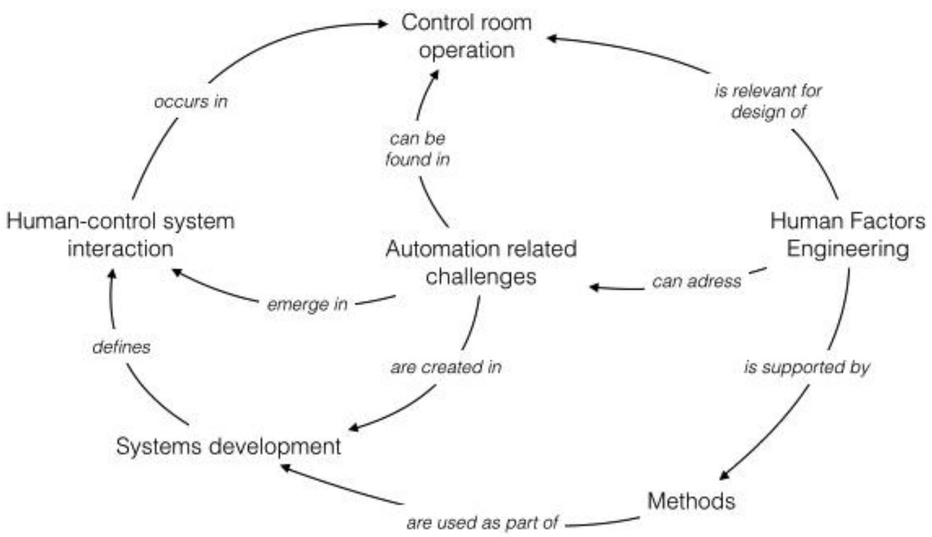


Figure 1. Research context

From the combination of understanding of situated work (e.g. from observations and interviews in the field) and theoretical knowledge, new designs should be proposed, preferably by using methods that provide results useful to other disciplines in the development process. By proposing new designs (e.g. ways for operators to interact with the control system) the human factors engineer is also likely to change the working practice, which motivates the use of prototypes and iterative development process to arrive at an appropriate design solution.

In my research projects, the challenges of automation and human-control system interaction were experienced both via empirical research studies (i.e. interviews and observations in industry), and through engineering practice. Through the industrial research projects I gained insights of the "apparent simplicity, but real complexity" (Woods, 1996) of how automatic functioning can be obscured by interfaces with poor transparency towards the underlying technical complexity. I have seen how seemingly simple technical sub-systems can create challenging tasks and demanding decision making, and how the implementation of support will alter work practices and demand for iteration. By working as a human factors engineer together with other engineering disciplines (e.g. automation engineers, process engineers and programmers) I have also obtained hands on experience of how ideas for solutions are constrained by both technical and organisational aspects. In retrospect, the recurring theme throughout my research has been how to deal with the challenges of interaction and cooperation between humans and technical systems in a way that is feasible in engineering practice in industry.

1.2 Problem description

The research problem in this thesis concerns how to describe and analyse automated human-machine systems. The reason for describing and analysing automated human-machine systems is to identify interventions that can inform the human factors engineering design process for such systems. In practice this means finding a systematic way of working to enable system designers to manage complexity by creating meaningful representations across a joint system that includes the dynamic technical domain, the control system and human operators.

1.3 Purpose and aim

The research work has been focused on how human-automation related challenges can be addressed to improve the preconditions for control room operators to comprehend automatic system functioning. Creating the appropriate preconditions for safe and effective work in control environments is a multidisciplinary design challenge. The **purpose** of this thesis was to aid human factors engineering practitioners in industry to deal with this challenge.

The **first aim** was to present a theoretically based model capable of representing normal interactions as well as associated operational problems in a human-automation system. The model should serve as a basis for how human-automation related challenges can be addressed.

The **second aim** of the thesis was to provide a viable tool for industrial human factors engineering practitioners. The tool should aid description and analysis of automated human-machine systems to address challenges related to human factors engineering of such systems.

1.4 Research process – to acquire understanding by shifting roles

Human factors engineering practitioners run into many collaborative challenges in their work (Kirwan, 2000). This is a result of the complexity of industrial domains, where many different competencies are required to achieve, operate and maintain purposeful and efficient work systems. Process engineers, automation engineers, programmers, human factors engineers, interaction designers, operators, management, etcetera, simply have to collaborate and all stakeholders have roles to play in how human-automation related challenges emerge and are dealt with. Researcher roles include outside observers and identifiers of different phenomena, and providers of new knowledge to direct efforts to what is perceived as important in order to solve problems. In the research process section, I describe the projects in different domains that have shaped my research efforts over time and how, by shifting roles, I could acquire an understanding of the research problem.

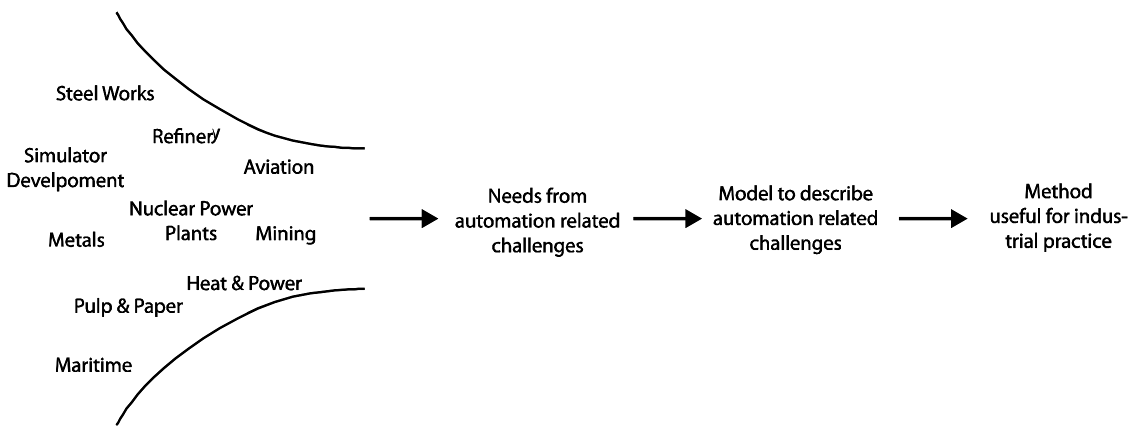


Figure 2. Research process

By experiencing many different domains I realized that, despite the differences between the domains and their characteristics, there are also striking similarities as to how people are affected by and manage the challenges posed by working in complex automated processes. In the visualization projects (see Table 3) in the later stage of my doctoral studies I worked actively with industrial partners to enhance understanding and operation of automated plants.

The automation related challenges I have seen operators cope with in their daily operations have been the main driver for my work. During my doctoral studies I have not committed to any particular research methodology or paradigm, although I have been inspired by Cognitive Systems Engineering (Hollnagel and Woods, 2005; Woods and Hollnagel, 2006) and action research (Reason and Bradbury, 2008), and lately I have realised the potential of interactive research (Svensson, 2002). The research has been conducted in an opportunistic way where the available research funding has, to a large extent, determined what domains and contexts have been studied. Rather than deciding beforehand, the approach has grown out of the preconditions under which I have done my projects, i.e. the ecology has shaped my work. The financiers of my projects have mainly been organisations that have expected research output useful in practice. Therefore the research presented in this thesis can be characterised as "mode 2" research, where knowledge is produced in a broad trans-disciplinary context with focus on practical application (Gibbons et al., 1994).

Table 2 summarises the publications that have been published in the different research projects in which I have been working.

Despite the research projects having been disparate and performed in different domains the context for my research has continuously been control environments in more or less complex industrial systems. These socio-technical systems are characterised by the human operator being there for the system (e.g. a power plant) rather than the system being there for the human operator (e.g. as in consumer products).

Table 3 summarises the projects I have worked in and lists the publications related to each project. Throughout these projects I have worked as part of a group of researchers devoted to the study of human factors engineering in practice.

Table 2. List of publications

	Publications / Research focus	Industrial needs	Control system interface design	Automation related challenges
	2008			
A	Andersson, J. & Osvalder, A. (2008) In Search for Common Ground - How An Automatic Turbine System Supports Operator Work. *European Conference on Cognitive Ergonomics 2008, 16-19 Sep., Funchal, Portugal*		X	X
B	Andersson, J. (2008) Levels of Automation and User Control - Evaluation of a Turbine Automation Interface. : Nordic nuclear research report NKS-179.		X	X
C	Bligård, L., Andersson, J., Thunberg, A. & Osvalder, A. (2008) *MMI-Design av systemlösningar i kontrollrum - Arbetsprocess för utformning utifrån ett människa-maskinperspektiv*.: Värmeforsk.	X	X	
	2009			
D	Andersson, J. & Osvalder, A. (2009) Levels of Automation and User Control in Use of an Automatic Turbine Interface. *European Conference on Cognitive Ergonomics 2009*		X	X
E	Andersson, J. (2009) NKS-R AutoNewTech: Levels of automation and user control - evaluation of a turbine automation interface. *Proceedings of the NKS-R and NKS-B Joint Summary Seminar, Armémuseum, Stockholm, Sweden, 26-27 March 2009*		X	X
F	Bligård, L., Andersson, J., Thunberg, A. & Osvalder, A. (2009) Graphical visualization of process status for thermal power plants. *Human Factors and Ergonomics Society Europe Chapter Annual Meeting*	X	X	
G	Bligård, L. & Andersson, J. (2009) Use errors and usability problems in relation to automation levels of medical devices. *European Conference on Cognitive Ergonomics 2009*			X
H	Osvalder, A., Bligård, L., Andersson, J. & Thunberg, A. (2009) Framework to describe and categorise a complex human-machine system. *Human Factors and Ergonomics Society Europe Chapter Annual Meeting*	X		
I	Osvalder, A., Bligård, L., Andersson, J. & Thunberg, A. (2009) *Utformning av kontrollrum för värmekraftverk och pappers- och massafabrik*. : Chalmers University of Technology.	X	X	
	2010			
J	Andersson, J. (2010) *A Conceptual Model for Analysis of Automation Usability Problems in Control Room Settings*. : Chalmers University of Technology.			X
K	Andersson, J. (2010) Using AcciMaps to describe the emergence of critical work situations - A systemic approach to analysis of automation. *In D. de Waard, Axelsson, A., Berglund, M., Peters, B. and Weikert, C. (Ed.), Human Factors: A system view of human, technology and organisation*			X
L	Andersson, J., Bligård, L. & Osvalder, A. (2010) Visualisation of automatic sequences - integration with process mimic display. *Proceedings of the International Conference on Control Room Design*		X	
M	Bligård, L., Andersson, J. & Osvalder, A. (2010) Design of an overview display for rapid perception of plant status. *Proceedings of the International Conference on Control Room Design*		X	

	2011			
N	Andersson, J. & Osvalder, A. (2011) *Automation strategies in five domains - A comparison of levels of automation, function allocation and visualisation of automatic functions*. : Nordic nuclear research report NKS-237.	X	X	X
O	Andersson, J., Bligård, L., Osvalder, A., Rissanen, M. & Tripathi, S. (2011) To Develop Viable Human Factors Engineering Methods for Improved Industrial Use. *A. Marcus (Ed.): Design, User Experience, and Usability, Pt. I, Human Computer Interaction International, Orlando FL 2011, Lecture Notes in Computer Science 6769* DOI: 10.1007/978-3-642-21675-6_41.	X		
P	Osvalder, A., Bligård, L., Andersson, J. & Thunberg, A. (2011) *Visualisering av anläggningsstatus - Utformning av innovativa gränssnittspresentationer*.: Värmeforsk Service AB.	X	X	
	2012			
Q	Andersson, J. (2012) A tentative model for analysis of human-automation interaction in control rooms. *2012 Proceedings of the ASME 11th Biennial Conference on Engineering Systems Design and Analysis (ESDA2012)*			X
R	Andersson, J. & Osvalder, A. (2012) Analysing work in complex industrial systems - A practical cognitive systems engineering approach. *Proceedings at the NES (Nordic Ergonomic Society) Conference, Stockholm, Aug 20-23, 2011.*			X
S	Berlin, C., Andersson, J., Fasth, Å., Grane, C., Abrahamsson, L., Johansson, J., Osvalder, A. & Stahre, J. (2012) Keyword Mingling workshop - a method for identifying and consolidating industrially perceived needs and requirements of future operators. *Swedish Production Symposium, SPS12*	X		
T	Bligård, L., Andersson, J. & Osvalder, A. (2012) Transfer of control system interface solutions from other domains to the thermal power industry. *Work: A Journal of Prevention, Assessment and Rehabilitation* 41, nr. Supplement 1/2012, s. 2859-2865. DOI: 10.3233/WOR-2012-0535-2859.	X		X
U	Grane, C., Abrahamsson, L., Andersson, J., Berlin, C., Fasth, Å., Johansson, J., Stahre, J. & Osvalder, A. (2012) The operator of the future – a key to competitive industry in a future information society. *Swedish Production Symposium, SPS12*	X		
V	Jamieson, G., Andersson, J., Bisantz, A., Degani, A. & Lind, M. (2012) Model-based approaches to human-automation systems design. *2012 Proceedings of the ASME 11th Biennial Conference on Engineering Systems Design and Analysis (ESDA2012)*			X
X	Osvalder, A., Andersson, J., Bligård, L. & Alm, H. (2012) *Impact of Physical Ergonomics Design of Process Control Rooms on Operator Experience of Comfort, Stress and Emotions.* : Chalmers University of Technology.	X		
	2013			
Y	Andersson, J. & Osvalder, A-L. (2013) Method characteristics for viable human factors engineering practice. Submitted to Applied Ergonomics.	X		
Z	Osvalder, A-L., Andersson, J., Bligård, L-O., Colmsjö, A., and Alm, H. (2013) *Operator Experience of Comfort, Stress and Emotion During Control of a Simulated Paint Factory – Impact of Physical Ergonomic Control Room Design*, Submitted to Human Factors and Ergonomics in Manufacturing and Service Industries	X		

Table 3. Summary of projects and publications related to each project.

#	Project	Description	Publications
1	HMI-Design of System Solutions in Control Rooms	The purpose of the project was to write a handbook to guide the HMI-design process in the process industries. The handbook was developed in collaboration with peers in domains such as pulp & paper, thermal power and consultancy. Obtained roles: Researcher – provider of existing knowledge	Publication C
2	Levels of automation and user control	The purpose of the study was to examine how operator performance is affected by varying levels of automation in nuclear power plant turbine operation. The evaluation pointed out interface flaws that hindered the operators' work and suggestions for improvements were made. Obtained roles: Researcher – interviews and observations of work systems	Publication A, B, D, E, J, K and Q
3	Automation strategies in five domains	The purpose of the project was to benchmark how automatic system functions are designed and displayed across five different domains. The results present what benefits the nuclear power domain can draw from other industries regarding automation and interface design. Obtained roles: Researcher – interviews and observations of work systems	Publication N
4	New bridge for the M/S Baltica	The purpose of the project was to develop a workplace with improved support for all aspects of the ship operator's tasks. The M/S Baltica is a vessel owned by the Swedish Maritime Administration and works with maintenance of the Swedish nautical fairways. For the rebuilding of M/S Baltica's bridge a new bridge concept was developed by means of a use-centred design process. The new bridge has been operational since spring 2011.	Nothing published

		Obtained roles: Researcher – interviews and observations of work system Human factors engineer – design and evaluation of concepts	
5	Visualisation of plant status	The purpose of the project was to design innovative operator displays for thermal power plants and pulp & paper plants. The project resulted in a number of operator-control system interface concepts that were evaluated with operators at the reference plants. Obtained roles: Researcher – interviews and observations of work systems Human factors engineer – design of interfaces	Publication F, H, I L, M, O, P and T
6	Evaluation of control room concepts	The purpose of the project was to compare two types of control room and evaluate the effects of physical control room design on operator performance. In the project a full scale batch process simulator was developed. Obtained roles: Process engineer – design of paint factory Human factors engineer – project coordinator Operator – testing and verification of functionality Researcher – design of simulator experiments, test leader	Publication X and Z
7	Operator of the future	The purpose of the first part of the project was to identify generic operator information needs in process and manufacturing industries in Sweden. Later parts of the project included the development of a toolbox for the industrial operator as a knowledge worker. Obtained role: Researcher – consolidation of industrial needs	Publication S and U

Figure 3 provides a timeline that shows the various research projects from Table 3 forming the empirical foundation on which the model and method presented in this thesis are based. Each separate project has had a specific goal and research questions, ranging from function allocation, levels of automation and graphical user interfaces to studies of collaboration and common ground. There have however, existed no overarching research questions that have guided the work over time. The joining factor for all projects has been the focus on how humans work with automation in different types of control centres.

From a traditional research perspective the multitude of projects might be seen as a great disadvantage in achieving focused research. However, I argue that the range of project agendas, the various domains, and foremost the various roles (see obtained roles in Table 3) that I have had to work in, has been a great advantage when discovering and understanding human-automation related challenges and the practical difficulties of human factors engineering work. The shifts in roles have given insights that would have been difficult to reach without first-hand experience.

Next, each project is briefly described. In addition, the roles I have worked in are also described, together with how my experiences have helped gain insight into the research problem.

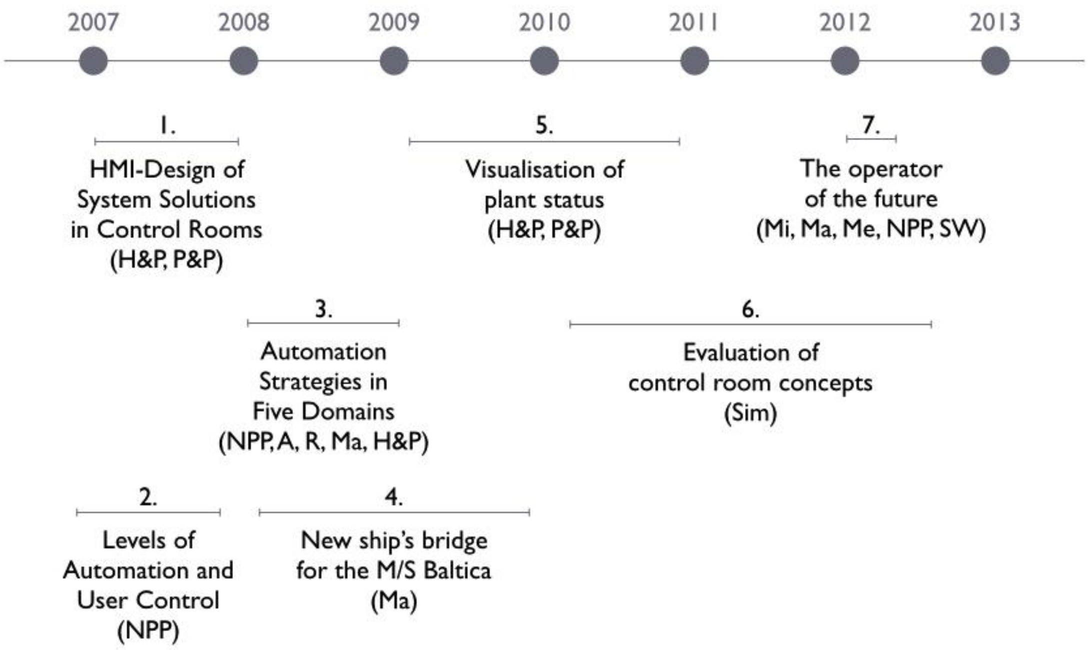


Figure 3. Projects and associated domains
(NPP: nuclear power plants, H&P: Heat & Power, P&P: Pulp & Paper, Sim: Simulator development, Mi: mining, Ma: maritime, Me: metals, A: aviation, R: refinery, SW: steel works)

In the HMI-Design of System Solutions project (1 in Figure 3) a handbook was authored for applied use in the heat & power and pulp & paper industries. The outline of the handbook was based on existing research, but the detailed content and examples were discussed and chosen based on the knowledge gathered from a number of experienced operators and engineers working at different plants in western Sweden. As part of a team of researchers I acted as a provider of existing knowledge of what was considered important at the time. The authoring of the handbook together with the feedback from industrial peers gave insights into what is needed for making research knowledge applicable in practice.

In the Levels of Automation project (2 in Figure 3) the research agenda was set in advance, but the choice of technical system in focus was decided in collaboration with subject matter experts. Operators were then observed and interviewed when using the turbine automation during their annual operator training in a full scope nuclear power plant simulator. The simulator environment provided the opportunity to study work and collaboration during critical operations in a realistic setting. In the role of a researcher I gathered information on how the operators' experienced the use of automatic functions. Their accounts of both usefulness and of perceived problems gave insights into the research problem from a realistic operational setting.

The Automation Strategies in Five Domains project (3 in Figure 3) was made as a field study with interviews and observations made in the aviation, refinery, heat & power, maritime and nuclear domains. In total nine different control centres were visited where function allocation strategies and visualisation of automatic functions were studied. By visiting the operators at their workplaces and during normal and hi-fi simulated operations, the operators could easily relate the questions asked to their working environment. The field study approach thereby facilitated the understanding of how contextual factors affect real working situations. In this study I had the role of researcher, and this project provided my first insights into that many aspects of automation related challenges are universal across domains, although the practical applications of control systems are different.

In the Bridge for M/S Baltica project (4 in Figure 3) the initiative to include researchers came from the Swedish Maritime Administration itself. The practitioners thereby set the scope of the problem. In the iterative design process mariners and project leaders were actively participating in the role of domain experts. By doing the research work on board the ship and later in the design stage by using increasingly realistic physical mock-ups, ideas could be effectively developed in collaboration with the mariners. As a researcher I conducted interviews and made observations of the how mariners work and the challenges they face as a result of how technology is designed. The scientific approach provided a systematic way of working, which gave a solid foundation to act on and the ability to follow-up on how the design solution shaped and improved the work system. As engineers, the development team involved the practitioners throughout the design phase. It was quickly realised we could not just tell such experienced mariners what we considered to be the best solution. Instead it was necessary to allow the mariners to work out and realise this by themselves. Therefore, a large part of the needs and requirements specification was done by taking a step back and facilitating the practitioners' own discussions. This approach effectively created credibility and acceptance for the final solution among the crew members.

The Visualisation of plant status project (5 in Figure 3) was highly interactive and included close collaboration with multidisciplinary teams at the plants where the results from the first research phase of the project were implemented. Through collaborative work in both need identification and design phase, a thorough understanding of the operational challenges was established. As a researcher, I conducted interviews and observations of operators in heat & power and pulp & paper plants. I also had the role of a human factors engineer when designing conceptual information displays. The human factors engineering role was further deepened in the collaboration with programmers, automation- and process engineers in a project team to implement a display for monitoring of a mixed lye subsystem in a pulp & paper plant. The team work gave insights into the importance and dependability of multiple competencies in human factors engineering work. In the project I also faced the challenges of how the context constrains how ideas and technical solutions can be realised in practice.

The Evaluation of control rooms project (6 in Figure 3) was initiated by a vendor of control room environments in collaboration with a vendor of control systems. In the different project phases my own roles shifted between researcher and practitioner. In the initial specification of the project I acted as a researcher in helping the company to define the study and what they could expect from the evaluation. As the project gradually became more defined, a traditional experimental within-subject study design was specified. Some variables of the environment were to be held constant, and others varied to reach conclusions based on scientific standards. After that, a simulator environment was designed and implemented and my role shifted to engineering practice. A fully functional paint factory simulator was programmed and the physical control room environments to be evaluated were set up. In this phase of the project I first acted as process designer of the paint factory with support from subject matter experts from a paint manufacturing company. After that I collaborated with two expert control system programmers to build a simulator and I continuously tested and provided feedback on the simulator from an operator's perspective. In parallel I coordinated the setup of the control room environments to comply with the specifications stated in the research design. Once the experimental environment (control rooms and simulator) had been built I returned to the researcher role. We then conducted experiments with fourteen experienced operators from various process industries, where I functioned as test leader. The project helped me further understand the complexity in operations, even in a small plant such as the paint factory simulator. I also experienced how it is possible to conduct research in staged worlds and how one can work to achieve the necessary realism. Regarding automation related challenges, I realised the flexibility of human problem solving and the importance of collaboration between operators to achieve fluent operations.

In the Operator of the future project (7 in Figure 3), the first part of the project in which I participated, consisted of gathering cross-industrial needs of future operators from two industrial groups; the process industry and workshop industry. To consolidate needs and reach consensus from two such large groups, the keyword mingling technique" was invented (Berlin et al., 2012) In this way, needs could be identified within many participants at once and in an interactive manner. The approach helped to gain insights into problems that are similar across domains, although the applications are different in detail. For example, communication, analysis, interpretation, and system control are skills (i.e. cognitive tasks) that are equally important across domains.

To summarise, I believe that the variety of projects I have participated in together with my research colleagues have helped me realise what is demanded of human factors engineering practitioners when they face automation related challenges in industrial settings. From working as a researcher, I have learned how to work with these challenges in a fruitful direction, while my practical engineering work has provided insights into the importance of making knowledge applicable.

1.5 Research approach

Based on the experiences from the applied research projects, the research approach is presented as a way of conducting research to find solutions to the problems experienced. First, practice centred research is presented as a scientific basis. Then, cognitive systems engineering is introduced as a tradition that provides a useful starting point for addressing human-automation related challenges.

1.5.1 Scientific basis – practice centred research

Solving problems and creating viable solutions in the industrial context is not an undertaking that can be completely managed by single engineers. Teamwork is needed, as experienced during the industrial projects in which I have participated. In that respect research has had close similarities to interactive research (Svensson, 2002). Svensson et al (2002) says the following about interactive research (translated from Swedish):

> "Interactive research is a research approach where the researcher creates knowledge together with practitioners. The starting point is to achieve equal and mutual relations where both researchers and practitioners are actively involved in the building of new knowledge. The purpose is to reach both theoretically insightful and practically useful knowledge. In dialogue with practitioners, the researcher can support a mutual reflection making different alternatives visible and the decisions of what the development work should focus on and what methods should be used are better grounded. The researcher works more problem- and dialogue based and adapted to local situations, as opposed to the more traditional solution and action based research approach. […] An interactive research approach has several advantages. It gives the researcher access to and understanding of the practitioners' own perspectives. Equal and reciprocal relations are a precondition for an open interchange of ideas. The diversity of opinions and the creativity that is supported through collaboration with practitioners facilitates the development of new theories. […] In interactive research the control is divided between the practitioners and researchers. The goal of common development of knowledge presupposes a close collaboration between the researcher and the participants and the stakeholders through the phases of the research process – in decisions of participation, research problem formulation, choice of methods, data collection, data analysis and in the presentation of results (Svensson, 1986; Svensson et al., 1990). The importance of close collaboration increases with the incompleteness of the researcher's knowledge of the problem to be studied. The collaboration and the roles can vary between the phases. A joint creation of knowledge ideally has great potential for both parties, although purposes and interests can vary. The research has the opportunity to become relevant, innovatory and offensive, as opposed to academic, traditional and defensive. The internal scientific discussion can be stimulated by creative and novel ideas in the generation of new theories and methods."

Svensson et al (2002) suggests the ontological combination of pragmatism and critical realism (Guba and Lincoln, 1994), as a way forward when building a foundation of interactive research. Pragmatism promotes the local and situated perspective of problem solving in a specific context and for a specific purpose (Johnson and Duberley, 2000). But according to Svensson (2002) the pragmatic approach is not enough to maintain high scientific standards. Without the ability to generalise and use the knowledge in other situations than those studied, the usefulness of the research effort could be questioned. Therefore critical realism is necessary as a complement. Critical realism belongs to a post-positivistic paradigm, where a reality is believed to exist, but we as human apprehend it imperfectly and probabilistically (Guba and Lincoln, 1994). In Cognitive Systems Engineering, Kirlik (2012) takes a similar standpoint to Svensson (2002), and argues for the need to perform research outside the laboratory in real world settings (local and situated). However, equal or more attention must be given to the practitioners' ecology, i.e. the environment where human cognition takes place. By describing the environments of perception, cognition and action it is possible to improve the preconditions for generalisation of findings in other environments (Kirlik, 2012). The importance of the ecological view is widely acknowledged within Cognitive Systems Engineering (Bennett and Flach, 2011; Hollnagel, 2005; Rasmussen et al., 1994; Vicente, 1999), which goes hand in hand with the perceived importance of conducting research "in the wild" (Hutchins, 1995). Based on the background described here, the methodological ideas of interactive research (situated but generalizable studies in collaboration with practitioners) fit well into the field of Cognitive Systems Engineering.

Interactive research, as described above, clearly separates the roles of "researcher" and "practitioner" as different persons in the research process. Within action research (Reason and Bradbury, 2008) it is however, proposed that the same person can occupy both roles. For example, the researcher becomes a part of a team of practitioners, and studies the work system while being part of it. The researcher can then introduce changes as a practitioner and reflect on the effects the changes create within the work system. The advantages are similar to those described for interactive research (research performed in context), but the person performing action research can occupy both roles simultaneously.

Cognitive Systems Engineering

The focus of Cognitive Systems Engineering is to understand how people and technology perform in their work settings and how the work system can achieve its goals and functions. The Cognitive Systems Engineering agenda is stated to be: 'how we can design joint cognitive systems so they can effectively control the situations in which they have to function' (Hollnagel and Woods, 2005). The functional view is not new in human factors research, although Cognitive Systems Engineering asserts that a shift of paradigm is necessary; moving from a disintegrated view of humans and machines to a joint systems view. According to Norros and Salo (2009), the idea that humans and technology form a functional unity, is older than the Cognitive Systems Engineering initiative (the first publications using Cognitive System Engineering as a concept was published in the early1980s (Hollnagel and Woods, 1983). Norros and Salo (2009) argue that current design pressures in today's society act as "a flywheel" for the paradigm shift, where the earlier information-processing view is no longer capable of handling the situated design and research challenges outside the laboratory that have to be faced in applied research. Woods and Christoffersen (2002) explain how understanding based on research can be acquired by studying applied settings (Figure 4). By studying practitioners in the field, an authentic understanding is obtained on which a research base can be built. The research is the basis for generation of new hypotheses of usefulness, which stimulates design of new technology. When introducing new technology, the field of practice will change as the artefacts alter how people work, and useful concepts can be found by means of an interactive design process.

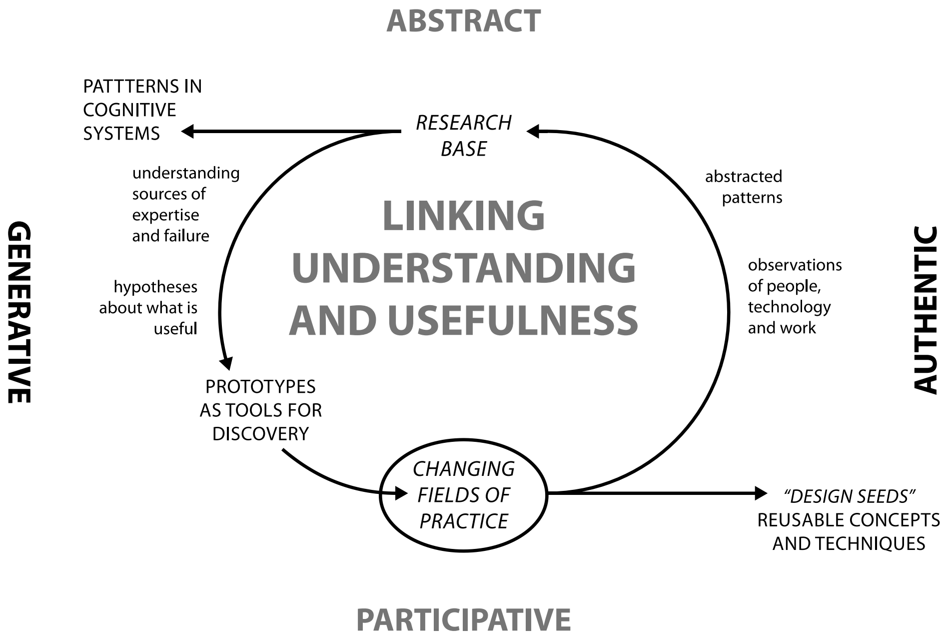


Figure 4. The relationship between research and practice is used to gain understanding and create useful designs. Adopted from Woods and Christofferson (2002)

Irrespective of which method an analyst or designer chooses to use, a systems perspective is essential to deal with the complexity in large scale industrial domains. According to Woods and Hollnagel (2006) a system perspective has three basic premises:

- A system's behaviour arises from the relationships and interactions across the parts, and not from parts in isolation.
- Understanding a system at a particular scale depends on influences from states and dynamics at scales above and below. Thus multiple levels of analysis are needed.
- How the parts of a system and levels of analysis are defined is a matter of perspective and purpose.

To some extent, these premises define what an approach to deal with automation related challenges must be capable of, i.e. representing a system with its relationships between parts, from different levels of abstraction and being able to account for different perspectives by asking the right questions. In the "outside the laboratory" respect, Cognitive Systems Engineering has provided a useful framework for the present research. The combination of seeing humans and machines as a joint system, together with the emphasis on applicable research, has provided a basis for the study of automation related challenges. For example, a number of guidelines based on Cognitive Systems Engineering research have been developed for human-control system design issues (section 2.7). There are also a couple of methods or frameworks that have influenced present research by paving the way for what seems like a fruitful approach to dealing with automation related challenges in control room settings (section 3.2).

1.6 Delimitations

The main delimitation of the thesis is related to the first aim of the thesis, i.e. how the human-automation system is framed. A “human-automation system” could be something very broad, but here it is used with a control room environment in mind, which means that the plant, the control system, the control system user interface and the operators are the main focus. Further, the social aspects in the human-automation system have not been subject to investigation. Therefore, the team aspects of control room work are not elaborated upon in the thesis.

1.7 Outline of thesis

The thesis starts with describing the foundation of the research effort, which is grounded in practical experience from research projects in collaboration with industry. This is followed by a description of an iterative method development process that starts from a theoretical model, goes through a requirement specification phase, continues with method design and ends in method evaluation. Each chapter is briefly described below.

Chapter 1 introduces the research problem, the research process and the practice centred research approach. Purpose, aims and delimitations of the thesis are stated, and a list of terms is given.

In Chapter 2 a model is introduced that can be used to describe human-machine systems. The model is expanded and adapted to process control, which enables description of automation related challenges in control rooms.

In Chapter 3, the questions a high utility method has to address to face automation related challenges are summarized and the research is contrasted to similar approaches in existing research. The strengths and weaknesses of existing approaches are highlighted and some aspects are incorporated into method development.

Chapter 4 defines criteria for development of a method that has the capability of addressing automation related challenges (solves the problem), is useful for human factors engineering practitioners in design, and at the same time is viable in an industrial development context.

Chapter 5 presents the System Representation Matrix as a method for analysing automated human-machine systems and representing automation related challenges. A systematic method procedure is proposed and examples of modelling and analysis are provided.

In Chapter 6, an evaluation of the method with industrial human factors engineering practitioners is presented. Feedback from practitioners is summarised in terms of both strengths and opportunities for improvement of the proposed method.

Chapter 7 is an assessment of how well the developed method has fulfilled the method requirements stated earlier in the thesis.

Chapter 8 contains a discussion of the thesis. The model and method developed in the thesis are discussed in relation to the intended use. Threats to validity throughout the research are also discussed. The main theoretical and methodical contributions of the research are also specified.

In Chapter 9 the general conclusions from the research are stated and the opportunities for further work are outlined.

2 Modelling automated human-machine systems

In chapter 2, a model is introduced that can be used to describe human-machine systems. The model is expanded and adapted to process control which enables description of automation related problems in control rooms. A number of automation related problems are presented as found in research literature. Each problem is followed by an explanation of the problem in the adapted model using the concept of incongruent variation. First, the research context is presented to frame the first part of the thesis.

2.1 Research context - framing the research

The experience base which this thesis builds upon has been gained through studies performed in different domains where supervisory control is a common denominator: Pulp and paper plants, heat and power plants, nuclear power plants, transatlantic ro-ro vessels, buoy tender vessels, oil refineries, transmission grids, paint factories, ship bridges and airplane cockpits are examples of domains with control centres that have been visited and operators have been interviewed. All of these domains make use of control systems to control, monitor and optimise the physical process that fulfils the purpose of the work system. The operators control the physical process either by acting directly upon the physical system or by using the control system. The physical process reacts on the operator's actions and sends information about the process status back to the operator, directly or via the control system interface. Environmental factors also affect the human-automation system in several ways. The physical process is, for example, constrained by the physical laws, humans are in turn constrained by for example cognitive abilities and patterns in social behaviour.

One of the effects of increasing use of automated sub-systems (i.e. control systems) is the change of operator roles from manual work to supervisory control (Sheridan, 2012). Tasks that previously were performed manually are now performed by the automatic systems that are supervised by human operators. This change causes new challenges to the operator. When tasks were performed manually the operator could more easily focus on one task at a time. With increasing use of automatic control systems several tasks are monitored simultaneously without need to intervene. Simultaneous tasks inflict higher cognitive demands and risks for various automation related problems. For example skill degradation, complacency, out of the loop problems and trust in automation (Lee, 2006). There is however no doubt that automation has been very beneficial to the process- and energy industries, with better means for effective and precise monitoring and control ("Britannica Online Encyclopaedia - automation," n.d.). The question is rather how automation technology can be used in a balanced way to avoid problems and maximise the benefit from technology in a safe way with respect to human abilities (Hollender, 2010).

2.2 The benefits of automatic process control

Automation, control systems and how it is used in process control is a large subject area to cover and this thesis deals with far from all aspects of it. Therefore I would like to clarify where the focus of the thesis lies in relation to the broad area of process control. In broad terms, the use of control systems in process control supports the storage, transportation and transformation of raw materials into products (Hollender, 2010).

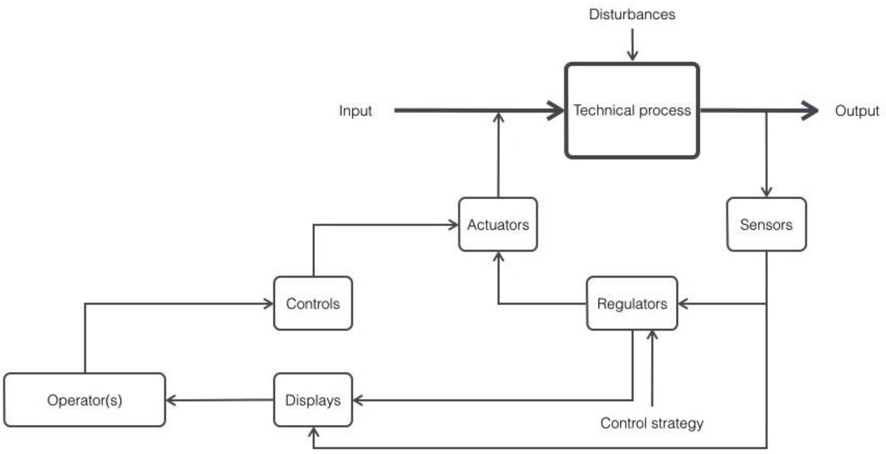


Figure 5. A simplified description of process control (Franzén (2014), personal communication)

Figure 5 provides a simplified description of basic process control where the technical process is controlled by actuators that receive information from sensors. The regulators allow the process to be controlled to desired state and for disturbances to be corrected. The process industries use a range of control strategies ranging from basic feedback / feed forward control and PID regulators, to advanced combined applications such as model predictive controllers, cascade control, neural networks, etc. (Lipták, 2006).

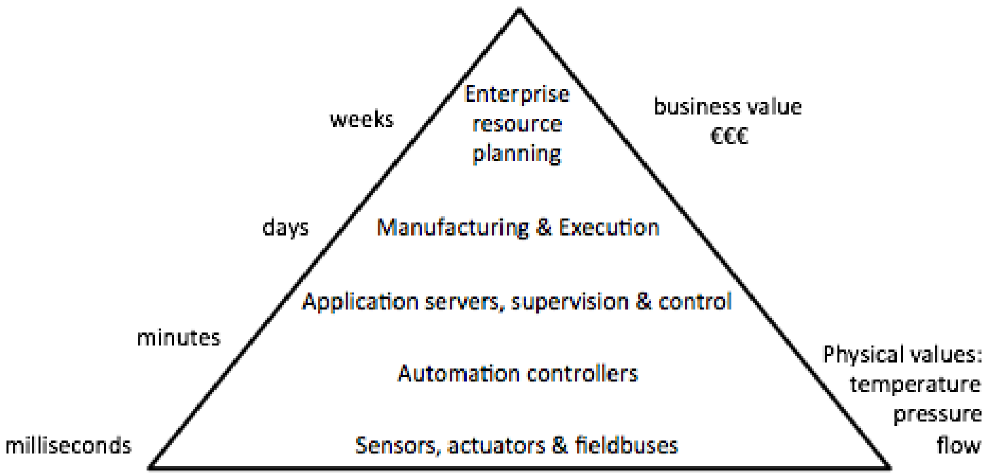


Figure 6. The Automation pyramid (Adopted from Hollender (2010))

Automatic systems are not only used in control of technical processes but also across managerial levels. The automation pyramid (Figure 6) show different systems that are related to the hierarchical level of a company. Moving from the bottom to the top the information become more condensed (Hollender, 2010). For example, thousands of measurements from the technical process are aggregated into key performance indicators and quality indicators used to determine the price of the end product. The ISA-95 standards describe four levels that are used to distinguish between automation layers (Figure 7). The current research work has only dealt with the lowest layer, according to the ISA-95 standard.

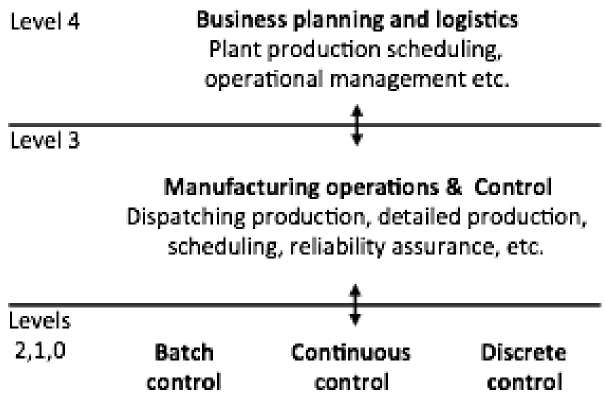


Figure 7. The ISA-95 functional hierarchy model (Adopted from Hollender, (2010))

This thesis does not deal with the higher levels in the ISA-95 hierarchy, i.e., levels three and four. However, I believe that the line of reasoning applied in the upcoming sections is valid also for the control system applications on managerial levels. The enterprise resource planning systems and manufacturing and execution systems have been introduced quite recently (Jämsä-Jounela, 2007). There is a potential that in the future there will be a corresponding set of automation related problems connected to higher organizational levels, if the challenges are not actively dealt with. Time will tell.

2.2.1 Operator roles in supervisory control

The use of automatic control systems means that tasks are transferred from manual to supervisory control. Historically, this has changed the role of the operators working in process control domains. Sheridan (2012) suggests five roles that the human operator has to engage in when interacting with automatic control systems: planning, teaching, monitoring, intervening and learning. First, the operator has to plan what the computer should do. Then the operator (or engineer) has to teach (program) the computer how to perform what has been planned. Next the operator monitors the control system's actions, and intervenes when the task is finished or interrupts to set a new goal state. Finally, the operator learns based on experience how to do things better in the future. In process control may not be as sequential as Sheridan suggests although all of the steps are present. For example, the time spent in the monitoring role can be prolonged for long periods of time while intervening and learning is done in parallel.

2.3 The triadic view of human-machine systems

The use of control systems by necessity creates the need for supervisory control, at least as long as a human is needed as a part of the process control production system. Supervisory control has been described in a number of ways in earlier research (Hollnagel, 1999; Sheridan, 2012; Vicente et al., 2004). In accordance with the cognitive systems engineering paradigm, Bennet and Flach (2011) suggests that supervisory control can be seen as a triadic-semiotic relationship between the dynamic domain, the control system and the human operator. The triadic-semiotic model emphasise the ecological view as described by for example Neisser (1976), Simon (1996) and Rasmussen et al (1994). The ecological view is important in process control applications since the process properties and behaviour is dictated by the laws of nature.

The ecological view emphasise the impact of how the constraints found in the actor's context shape the actor's behaviour. For instance, Simon (1996) exemplifies the impact of the context by the analogy of an ant moving around on a beach. When the ant is looked upon in isolation its behaviour looks complex as it is moves around on the beach. Hence, one might believe that the ant therefore also embodies a complex cognitive process. However, if you look at the ant+beach as a an actor moving around in its context the behaviour seems natural as the beach with obstacles shape the ant's path by imposing behavioural constraints. Similarly, human behaviour is shaped by constraints that can be of for example social, technological or organisational nature. By analysing the actor's working domain (i.e. "the beach") the constraints can be revealed and behaviour understood and also to some extent predicted.

The triadic model describes the simultaneous dynamics occurring between the actor, the information medium and the ecology (Bennett and Flach, 2011). The model can be illustrated by giving two examples from medicine and process control. In medicine, the situation of a doctor treating a patient where the 'ecology' is the patient, the 'medium' is the symptoms of the patient and the 'actor' is the doctor with all the acquired knowledge of contemporary medicine. Typically, the doctor will listen to the patient's story and look at her symptoms forming a belief of what might be the problem. With the intention of curing the patient a medical treatment is assigned (performatory action)[1] based on the symptoms (representation). At the same time the doctor may explore how the patient responds to the treatment (exploratory action). The doctor monitors (observation) if the treatment changes the patient's state (consequence). The change (or lack of change) in symptoms tells the doctor if the treatment seem to have the intended or any unanticipated effect (error) or if another disease might be the problem (surprise). In the example of medical treatment the symptom is a representation of the actual sickness. For example a combination of blood samples can show patterns of disease that is not detected from the patient's general health condition, providing a complementary representation of the disease. The triadic semiotic model is shown in Figure 8.

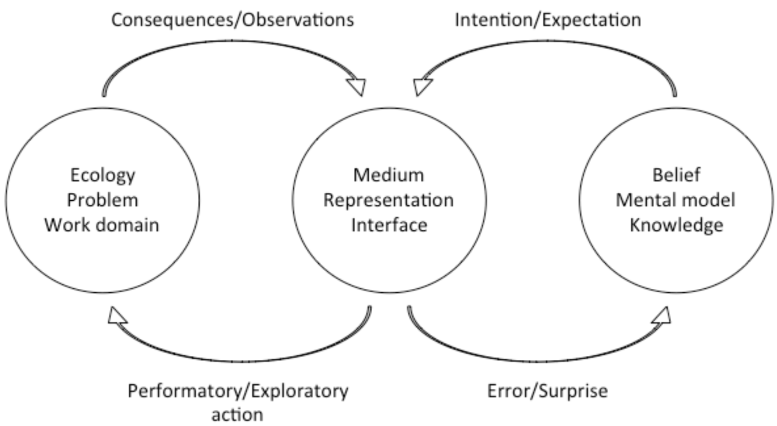


Figure 8. The triadic-semiotic model as presented by Bennet and Flach (2011)

As an additional example, operation of a heat&power plant boiler can illustrate the triadic model. Here, the physical work domain is represented by 'ecology', while the control system interface together with the means of controlling the plant locally on process equipment is represented by the 'medium'. A skilled operator has an extensive conceptual model of what the plant looks like and how it works, represented by 'belief', 'mental model' and 'knowledge' in Figure 8. The goal (intention) of the control room team of operators is to burn material in the boiler efficiently to optimise how energy is converted to heat and electricity.

[1] Model components are written in brackets

Using the control system interface they can monitor and control the process to fine-tune the combustion process. By adjusting variables (performatory action) for example air flow, fuel flow, chemicals and water injection, emissions can be kept within prescribed limits. At the same time the operator explores how the combustion process reacts to different alterations (exploratory action) since the optimal setting may differ for example due to unknown variations in fuel quality. The combustion process is measured revealing the consequences of actions and returning observations of the alterations which are presented in the control system interface. The result of process alterations will on one hand try optimise the combustion (minimise error), and on the other hand change the operators' model of the combustion process as new knowledge is gained (surprise) when the old conceptions of the process dynamics have to be updated.

The triadic model captures the so called regulator paradox (Bennett and Flach, 2011, p. 30). The paradox is that in a changing environment, a regulator must simultaneously function as both a controller and an observer. Acting as a controller, the agent forms an intention based on its belief, and acts through the medium with a performatory action on the work domain. The work domain produces a consequence of the action which is represented through the medium, and the agent can perceive the result as a successful (reducing error) or unsuccessful (increasing error) action.

Acting as an observer, the agent has an expectation of how the work domain behaves. The expectation can be tested by performing exploratory actions through the medium. The work domain response yields an observation which is perceived through the medium. The response is either expected, which confirms the agents model of the work domain or unexpected which creates surprise and an impetus to learn and change the current mental model. The controller and observer functions are active simultaneously in the human-machine system since a performatory and an exploratory action can be the same physical action, but the physical action has double objectives, e.g. both produce an intended consequence (controller) and test ones hypothesis of how the domain responds (observer). With the meaning of representations as a key pillar, the triadic model as proposed by Bennet and Flach (2011) has its foundation in semiotics (in Peirce's tradition).

The triadic semiotic model and the model of the human-control system-technical process describe different views of the same thing (Figure 9). The Technical process corresponds to Ecology, the Control system and HMI corresponds to the Medium, while the Human operator corresponds to Mental model in the triadic semiotic model. The regulation model depicts the physical entities in the human-machine system while the triadic semiotic model focuses on the process of creating meaning in a human-machine system. The knowledge needed for control can also reside in the regulator as an instance of the designer's intention of how the technical process should be controlled. The regulator contains a model of the technical process. From the operators perspective the control system is however foremost a medium that enables remote supervisory control of the technical process.

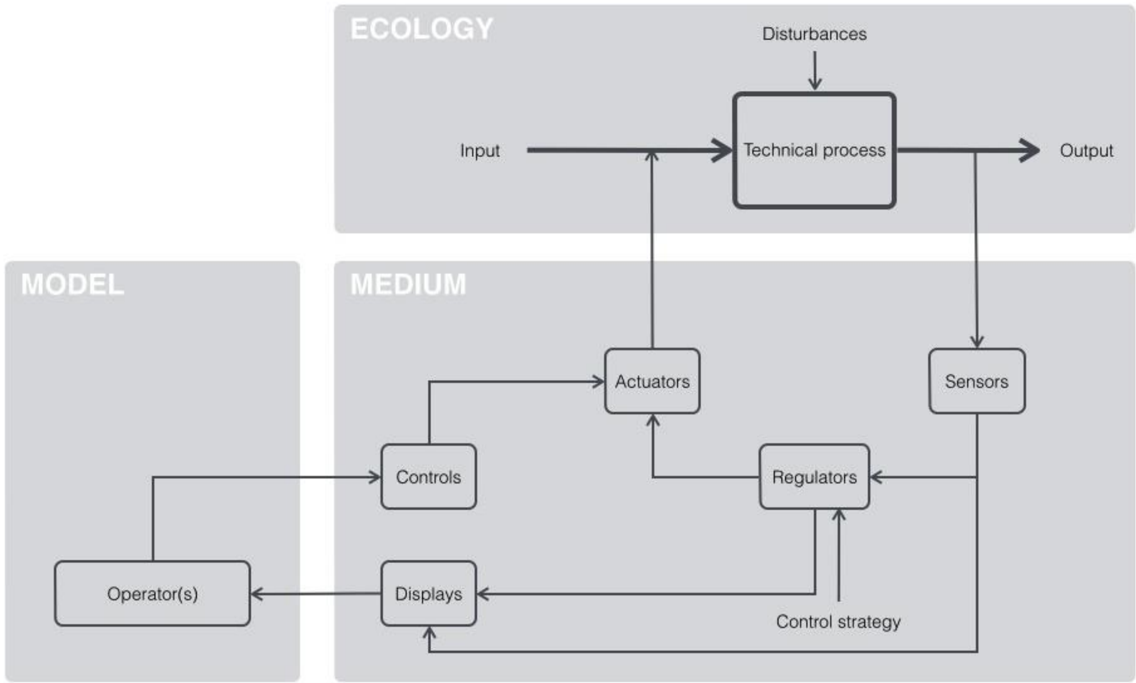


Figure 9. The triadic model overlaid on the traditional regulation model

2.3.1 Ashby's law of requisite variety

With the Law of requisite variety, Ashby (1956) showed that a controller must be at least as complex as the problem being controlled, or there will be regions of the problem space that will be unreachable (Flach, 2012). This means that unless the model that is accessible to the operator by internal and external representations is complete, situations can occur when the ability to maintain control will be lost.

To create representations to support control of a dynamic domain and its control system means that the representations have to model the complexity, in other words obey to the law of requisite variety. In practice this means that to handle complexity and be sure to maintain control, the controller's model of the world has to be at least as complex as the world to ensure control in all possible events. In a later publication Conant and Ashby (1970) expressed the same idea as "every good regulator of a system must be a model of that system", and this expression is directly transferable to the process control domain. In process control there are at least two broad types of controllers, the human operator and the control system. The complexity or variety of the process is determined by the ingenuity of the engineers and the laws of nature as the process is designed to produce an outcome (such as electricity or a chemical product). The complexity is set since it is needed to achieve a specific goal, although the engineering solution can make things more or less complicated. The control system presents a simplification of the process depicted in the control system interface which is used by the operator to perform control actions and monitor the factory. The control system and the control system user interface representations have to model the domain with sufficient functional adequacy or control strategies will be brittle due to oversimplification (Conant and Ashby, 1970). Similarly, the operator's understanding of the interface and the dynamic domain must be sufficiently detailed, or else decisions taken on a simplified model might lead to unexpected results. It will also be difficult to optimise production if the internal workings of the process are not thoroughly understood. The ecology of the work domain determines what actions will be possible to perform and how they can be performed.

In process control, the work domain constraints consists of, for example, the laws of nature and the control system's abilities. In analogy with Bennet & Flach's triad (Bennett and Flach, 2011), process control can be seen as a triadic relationship between ecology (dynamic domain), medium (control system + interface) and agents (operators). The control system can however, also be seen as an agent as it acts autonomously. The property of automation is inherent in the control system, which creates the need for supervision.

In complex dynamic systems there will always be gaps in models (Hoffman and Woods, 2011). These gaps have to be filled to maintain control when operations require additional variety, for example, in a case of an unanticipated event. In complex systems operators have to continuously adapt and be proactive to maintain an updated view of the system state (Mumaw et al., 2000). Operators' initial education, reoccurring training and continuous work during normal operating conditions will only maintain part of the knowledge needed in a continuously changing environment. Thus the 'observer' function is important to detect and enable adaptation when the work situation changes into a previously unknown or infrequently occurring situation. The more complex the domain and the control system becomes, the higher the need for the joint system to rapidly adapt to new operating conditions.

2.4 Adapting the triadic model to process control

The triadic semiotic model can be used as a basis to describe and be able to address challenges related to use of automation in process control. I will now suggest some modifications to expand the triadic semiotic model in order to cover the specifics of process control. The modified model presented in Figure 10 is still a coarse simplification, but despite this valuable for addressing the automation related challenges in the upcoming sections.

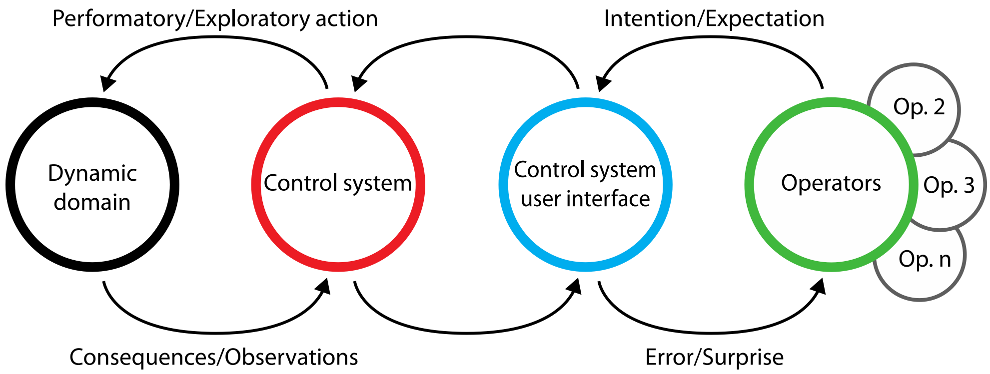


Figure 10. A model describing process control

In Figure 10 the control system and the human-system interface is separated. The 'ecology' here is delimited to the controlled dynamic domain. (For example, organisational issues are not included as a part of the model.) The parts of the model are intertwined with each other. For example, the control system interface is part of the control system. It is also difficult to separate the control system and the dynamic domain completely.

The Operator circle

In process control, the operator initiates a control action by acting in the control system interface. The action can be a response to information perceived from the interface, a result of an external event (e.g. directions from production planners or management) or based on a decision made from the operator's inherent knowledge (conceptual model). The operator can teach the control system what to do in terms of giving input that the control system uses to perform actions. In the case of highly automated processes, the operator monitors the dynamic domain and intervenes in the event of deviations from the production envelope. Deviations and failures (as well as maintaining system state) will invoke learning on the behalf of the operator that will develop the operator's conceptual model further and expand experience.

The operator can have different roles in supervisory control, such as planning, teaching, intervening, monitoring and learning (Sheridan, 2012). Planning, teaching and intervening are examples of controller function where performatory actions are executed. Monitoring and learning are examples of observer function as exploratory action yield feedback and opportunities for learning.

The Control system interface circle

The control system interface is the operator's window to the plant, making it possible to perceive the dynamic domain remotely. Hence, the information displayed needs to represent the dynamic domain, so that the long term conceptual model (e.g. domain structure) and the short term mental model (e.g. fluctuating process values) of the operator are maintained. An important role of the control system interface is to provide the possibility for operators to maintain a sufficient match between what is happening in the dynamic domain and their own inherent model of what is happening. Maintaining a match is dependent on how correctly and timely the model can be updated in accordance with the dynamic domain variations, which is facilitated by and dependent on how the information is presented in the control system interface.

The Control system circle

The main purpose of the control system is to regulate the process equipment to maintain the dynamic domain within (safety) boundary conditions and also, preferably, within the span of optimal production. The control system counteracts dynamic domain variations, often by closed loop control. Control can take place at different levels, e.g. at the object level or at an aggregated level, such as control of groups of objects. Control loops are often nested (output affects other control loops feeding back to each other), which means that it can be difficult to grasp how the control system works in detail just by looking at the control actions and their response.

The Dynamic domain circle

The Dynamic domain circle refers to the system being controlled, meaning that the control system acts with the equipment in the dynamic domain to keep it within its boundary conditions. To detect the result of a control action, the control system measures what the control actions have achieved and adjusts its action according to feedback. In process control, the plant often consists of a myriad physical process equipment objects. The physical objects enable activity to fulfil functions needed to reach the goal of the dynamic domain (e.g. a pump enables flow used for cooling, which is needed to maximise production).

2.5 Model incongruence in operator-control system-dynamic domain interaction

Ashby's Law of Requisite Variety (Ashby, 1956) implies that the complexity of the controller will delimit how well the system can be controlled. In other words a controller of a system must be a model of that system in order to control it (Conant and Ashby, 1970) A too simple controller will not be able to sense all variations in the controlled system and thus cannot, by definition, control all dynamic domain variation.
In the process industries, the dynamic domain is as intricate as needed to produce the correct product. Process dynamics and complexity cannot be reduced by more than allowed by the desired production. Thereby, the complexity required of the control system is determined by the complexity of the dynamic domain. The operators as a team in turn, need to possess a model of the dynamic domain <u>and</u> the control system to be able to handle all types of variation. The main resource to keep this dynamic domain+control system model up to date is the information perceived from the dynamic domain and the control system, either in the control room or in the field.

The dynamic domain will exhibit natural variations, for example, due to fluctuations in raw material or the randomness of chemical reactions or physical processes. The control system needs to account for these variations, i.e. the control model has to be sufficiently complex to detect, decide and act on variations. If the dynamic domain moves outside the control system's boundary conditions, there is a risk of loss of control. If the dynamic domain changes, the control system has to adapt together with the operator in terms of understanding the new dynamic domain state.

2.5.1 What does incongruent variation lead to? Gaps between models

As stated in the previous section, if the human models of control do not match the dynamic domain to be controlled and how the control system behaves, the result will be a mismatch between models. The model mismatch can be described as a struggle to adapt to the variations of the system as a whole. Consequently it follows that the effort to maintain matching (mental and conceptual) models is equal to adapting to and understanding the continuous variations in the dynamic domain and in the control system.

The question is, what happens when there are mismatches between models? First, we need to define what is meant by a mismatch. If no mismatch exists, the models of the dynamic domain are identical across the triad down to the finest grain. In practice, this identical match will never occur, since the dynamic domain changes continuously, and because human and control system cognitive processes (i.e. perception, decision and action) are limited. The agent cannot perceive all dynamic domain changes in detail and neither can the control system, due to limitations in measurement. A model is per definition always a simplification, but as long as the mismatch due to system dynamics does not conflict with the purpose of the system, a mismatch of fine grained level of detail is of little relevance and will not compromise system performance. However, if the dynamic domain deviates outside of boundary conditions and countermeasures are taken based on an outdated model, the actions to correct deviations can lead to unintended outcomes.

In the previous sections it was shown how the emergence of automation related problems can be described as an incongruent variation between models in the dynamic domain-control system-operator triad. Next, the effects of incongruence between system parts are further explored by analysing the relative model match between system parts (Figure 11).

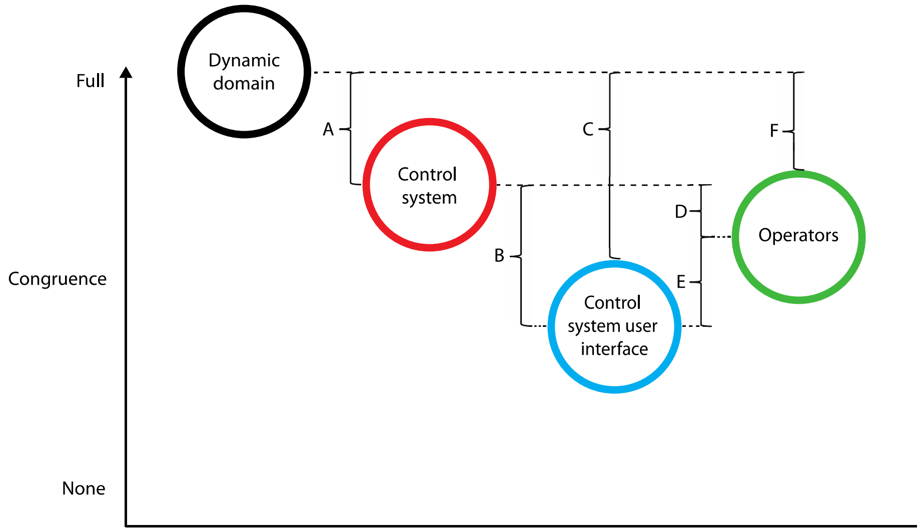


Figure 11. Gaps in model congruence across the dynamic domain-control system-operator triad (example)

Figure 11 shows the same entities as used in the model to describe process control. The Y-axis represents the level of congruence ranging from full congruence to none at all. The intention of the figure is <u>not</u> to establish an exact measure of congruence, but rather to illustrate more clearly the effect that variation of model congruence might have.

Table 4. Explanation of Figure 9

Circles	Circle content
Dynamic domain	The controlled domain with full complexity and dynamic behaviour.
Control system	The control system's (control) model of the dynamic domain.
Control system user interface	The control system's visual representation of the controlled dynamic domain and the control system communicated to the operator
Operators	The operators' descriptive knowledge of what the Dynamic domain and the Control system contain and how they function together to achieve the goal of the Dynamic domain. The operators' procedural knowledge of how to operate and monitor the Control system by using the Control system interface to perform actions on the Dynamic domain. The operators' general knowledge and experience from other domains relevant to achieving the goals of the Dynamic domain.

The illustrative placement of the circles in relation to the Y-axis in Figure 11 shows an example of how model congruence could appear where automation related problems emerge. In other words, the control system could possess the best match to the dynamic domain, while the operators have a poorer mental model of the dynamic domain and control system (this is of course, not necessarily the case, but is used as an example). In a plant with high probability of emerging automation related problems, the control system user interface as an external representation will only represent some parts of the dynamic domain and the control system, and only to some extent support operator knowledge. The relations between the models and how the gaps in Figure 11 emerge can be used to reason about why automation related problems emerge and what can be done about them.

Gap A in Figure 11 illustrates the underspecified control system model of the dynamic domain. Gap A will never be completely closed, but a sufficient match can be achieved in relation to the specific system goals to be met (for example linearization). Gap B and C represent how well the control system user interface can represent the control system and the dynamic domain respectively. Gap D represents the mismatch between the operators' mental models and how the control system works. Gap E represents the potential mismatch between the operators' internal representation and what is shown in the control system user interface. Gap F represents the operators' underspecified model of the dynamic domain. (The relations depicted in Figure 11 are hypothetical and used to illustrate describe automation related problems and not exact measures based on empirical findings.)

Given that the idea of using model congruence to describe automation related problems is valid, a strategy to reduce problems can be to first minimize the gaps to improve the preconditions to avoid problems, and secondly to develop strategies to cope with the gaps that maintain work system fluency.

From interpreting Figure 11, it would seem the most powerful remedy would be a reduction of excess complexity in the dynamic domain, since this strategy would facilitate the reduction of gaps A, C and F simultaneously. This approach is however, strictly bounded by the technological complexity and natural laws needed to achieve a functioning work system. The bounds dictate the preconditions of production in the work domain.

Different measures can be taken to reduce the gaps, but every attempt to improve the match will come at a cost. For example, the dynamic domain-control system congruence can be improved by clever process modelling. However, more advanced control loops will increase the complexity and possibly increase the gap to the user interface and operator entities (gaps B and D). Reduction of the control system complexity has been suggested as a way to facilitate operator understanding (Jamieson and Vicente, 2005). The intention of this approach is to reduce the control system-operator model incongruence (gap D). According to Figure 11, the reduction of complexity may however come at the cost of having to increase the gap between dynamic domain and control system (gap A). Naturally, the feasibility of the approach depends on the trade-off to reduce complexity without over-simplifying the control system's model of the dynamic domain (i.e. compromising the ability to optimise).

To reduce the incongruence of the control system user interface (gaps B, C and E), one approach is improved visualisations. Gap B depends on how (and if) control system logic and functionality is presented in the user interface. Visually representing control loops that can be nested, cascading and interdependent in work domains that can contain thousands of objects is a challenge and requires a systematic approach. Likewise, the controlled dynamic domain itself has to be represented (gap C), which is limited by, for example, the available number of sensors that can provide input to reflect what is going on in the plant. The inherent complexity in the dynamic domain will also pose challenges to visualisation, e.g. representing the physical process in relation to stoichiometric combustion and thermodynamics. A gap between the control system user interface and the operator's model (gap E), as shown in Figure 11, implies that the operator has a more developed internal representation of the controlled dynamic domain than given through the user interface. The operator's representation can be developed from theoretical education, training and foremost from practical experience of work in the field (i.e. tacit knowledge).

The gap between the operator model and the control system (gap D) depends on how well the operator understands the control system. The operator can have a better model of the dynamic domain than the control system contains, e.g. as a result of experience from manual control or from having worked with or developed control system logic. Experience from control system development could be reasonably expected to reduce gap F, since control engineering simultaneously improves knowledge about the dynamic domain.

The gaps between the models that the system parts each contain (as expressed in Figure 11) will never be entirely closed. Since there is always a need for simplifications in a work system with finite resources, the difficulty is to know when simplifications can be made without compromising the work system's safety or overall performance. The dynamic domain will change continuously and each update of other parts will therefore lag. Furthermore, exploring the system from one perspective will, at the same time, obscure other perspectives and it is impossible to see several perspectives at the same time. Hoffman and Woods (2011) express these law-like conditions as bounding constraints on macro-cognitive work systems. The gaps, which I claim can lead to automation related problems, arise due to these constraints, but the existence of gaps is, at the same time, the normal state. In a sense, the gaps are simultaneously a source of problems but also the reason the work system functions fluently. Without simplifications the work system would quickly become very inefficient owing to have to struggle with the overwhelming complexity in every detail of reality. The difficulty is to interpret signals of when simplification is no longer sufficient to maintain safety and performance, and to see when a switch has to be made to more complete models (Hoffman and Woods, 2011).

2.6 Automation related problems in process industry control rooms

In this section automation related problems will be described as in scientific research literature. The section introduces potential problems that emerge when humans and control systems cooperate to achieve a common goal. Research regarding how automation affects work system performance, has primarily been performed in the aviation domain, and also in process control, shipping and medicine. The problems are described and examples are given of how they emerge and the possible consequences that may result.

Each problem description is followed by a problem explanation using the adapted triadic model. Each problem can be understood as gaps emerging between the dynamic domain, control system or operator part of the joint operator-control system-dynamic domain triad. It is shown that when gaps due to incongruent models occur in the system (e.g. one system part changes differently to another corresponding part) this will lead to ‘automation related problems’. In Figure 12 to Figure 19 the adapted triadic model is used to illustrate each automation related problem as model incongruence. Where applicable, each description is followed by an example from my own studies.

2.6.1 Clumsy automation

Clumsy automation can be defined as poorly designed control system technology that makes easy tasks easier and hard tasks harder (Wiener, 1989). Wiener (1989) found that the aeroplane’s control system caused pilot workload to increase rather than provide support when workload reduction was needed the most. This was caused by the automatic features being too difficult to use in situations already high in cognitive workload. The pilots switched the flight management system off and reverted to a lower level of automation. This strategy however means that the useful features of the flight management system are also lost (Billings, 1996). Bainbridge (1983) also stated that it is often the easy tasks that are automated, while the difficult tasks are left to the operator to deal with. A reason for difficult tasks being left out, is that the control system designer is unable to think of how to automate the difficult tasks. The end result of this can be that the control system makes the operator’s job more difficult, rather than providing assistance.

Clumsy automation represented as model incongruence

Wiener’s description of clumsy control systems indicates that the operator has a difficult time understanding the control system’s action. One explanation as to why this happens is because the operator’s mental model is insufficiently developed i.e. the operator’s model is not congruent with how the control system works (Figure 12). Additionally if the operator needs to perform difficult left-over tasks as Bainbridge suggests, the operator’s chances of performing exploratory actions to learn how the system works are probably small. Also, the inability to appropriately represent the structure and function of the control system in the control system user interface, further worsens the operator's likelihood of being able to understand what is going on.

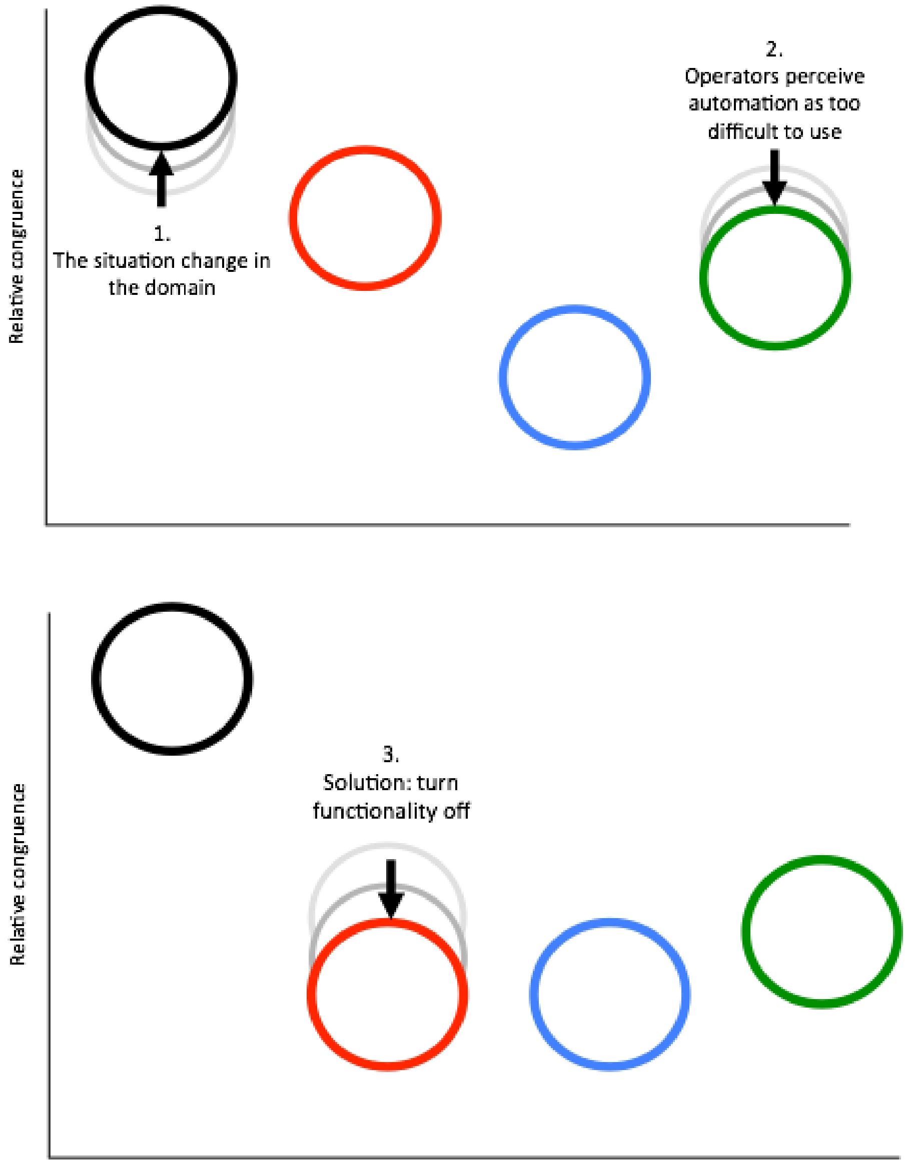


Figure 12. Clumsy automation

Normally the operator has a sufficiently good understanding of the control system. However, as the situation in the dynamic domain changes, the operator perceives the control system as being too difficult to use. The operator responds to this situation by not using or turning control system functionality off, in order to reinstate understanding of what is going on and to stay in control.

From the triadic-semiotic perspective, "clumsy" automation will remove the ability to explore and learn the dynamic domain and the control system since performatory actions are easily automated. The operator has to form intentions and expectations based on knowledge that cannot be based on working experience and feedback from observations of how the automatic functions behave. By reverting to manual control, the operator removes one layer of the medium (the automatic control system) to be able to observe how actions lead to performatory actions and exploratory actions lead to consequences.

In Figure 12, clumsy automation is described in terms of changes in the gap model. As the situation changes (1), the dynamic domain demands adaptation by other system parts. Without adaptation, the gaps in the dynamic domain will be stretched further. If the control system is ”clumsy” the operator will perceive the automatic functions as unhelpful (2) and eventually revert to disuse (Parasuraman and Riley, 1997). By turning control system functions off, the operator reduces the perceived incongruence and creates an understandable and manageable working situation (3).

In the nuclear power domain, Andersson (Andersson and Osvalder, 2009) found examples of clumsy automation in the operation of turbine automation. In operations using automatic start-up and shut-down sequences, turbine operators avoided high-level automation. The automatic turbine system made easy tasks easier, i.e., the manual start and stop of individual equipment and functional groups were made easier with automation. While hard tasks became even harder, i.e., trouble shooting in case of a failure in the sequences were obscured, since the control system interface did not indicate where the failures occurred on a sufficiently detailed level.

2.6.2 The out-of-the-loop problem

The out-of-the-loop performance problem has been defined as ‘automatic system operators’ diminished ability to detect system errors and subsequently perform tasks manually in the face of automation (i.e. control system) failures’ (Endsley and Kiris, 1995).

The emergence of the out-of-the-loop problem depends on a number of factors. Firstly, a high level of automation may reduce the feedback from the controlled dynamic domain. Since control room operators are monitoring and controlling from a distance, the direct physical feedback is reduced compared with locally performed manual control. The available feedback is then reduced to the information presented through the control system interface and what is received through communication with field operators. Secondly, a high level of automation puts the operator in a passive observation of the dynamic domain rather than active control, which puts higher demands on operators to maintain their vigilance. Automatic control also means that operators have time to engage in other tasks than just monitoring the controlled dynamic domain. This means that attention is directed elsewhere than the control system, which may make it difficult to follow how situations evolve.

Due to reduced feedback, passive observation and directed attention, the out-of-the-loop problem also leads to reduced situation awareness (Endsley et al., 2003), meaning that the operator does not know what has happened in the past, has a poor understanding of what is happening at the moment and will have difficulties in planning and deciding what to do next.

Early detection (before alarm) of deviations depends on knowledge of normal domain behaviour, i.e. a mental model of the controlled dynamic domain. This knowledge may diminish over time, due to the reduced need for close monitoring of an automatic process and the diverted attention. The skills needed to take over the tasks performed by the control system are also likely to go unpractised when the control system functions as it should. This makes it difficult to detect deviations and resume manual control if the control system fails, thus leading to out- of-the-loop symptoms.

Operators can however, very well be out-of-the-loop and still perform excellently in terms of production goals and low number of incidents. It is when the situation demands detection and action (often in critical states) that deteriorated abilities become observable. Moreover, it is not until problems are observed that they can be attributed to an appropriate cause (e.g. poorly presented feedback from the control system interface). As operators detect problems and search for solutions, they work themselves back into the loop until the situation is solved (Rasmussen, 1986).

The out-of-the-loop problem represented as model incongruence

Out-of-the-loop situations can emerge in (at least) two different ways. In out-of-the-loop (I) (Figure 13), the dynamic domain changes and the operator is unable to follow due to insufficient or inadequate information in the control system interface. In out-of-the-loop (II) (Figure 14), the control system performs the control and monitoring function so well that the operator can do other things, resulting in a loss of continuous update on what is happening. In some sense the out-of-the-loop (II) effect can be part of the purpose of automation in terms of relieving the operator from attention demanding tasks. If something goes wrong it can, however, be difficult for the operator to re-establish their awareness of what has happened.

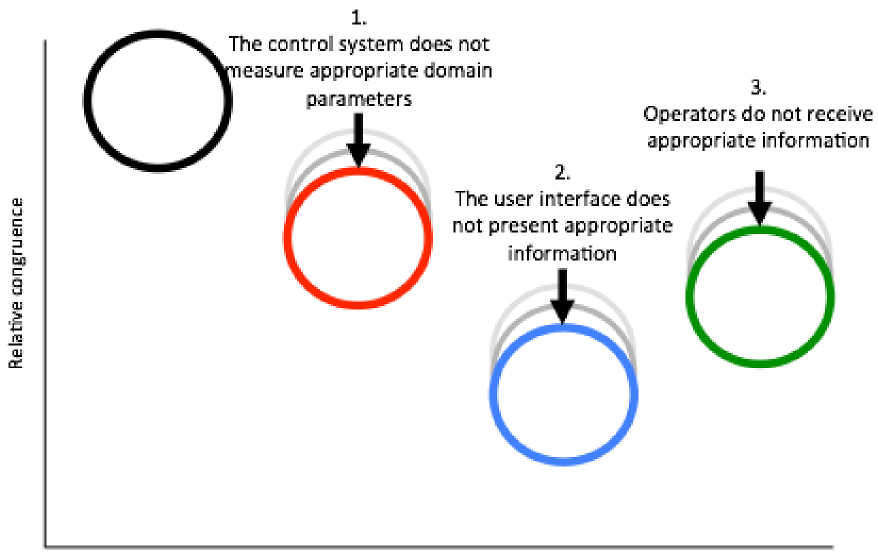


Figure 13. Out-of-the-loop (I)

In out-of-the-loop (I) the user interface does not contain the appropriate information with which to monitor and understand the dynamic domain and the control system (1). The lack of appropriate information in the user interface leads to the control system failing to communicate all situations to the operator (2+3). In the transition leading to out-of-the-loop problems, the gap between the domain and the control system will increase if the control system is incapable of sensing and combining data relevant to the current situation. This gap propagates into a gap between the control system user interface and the operator, since the information in the user interface is dependent on appropriate data from the control system.

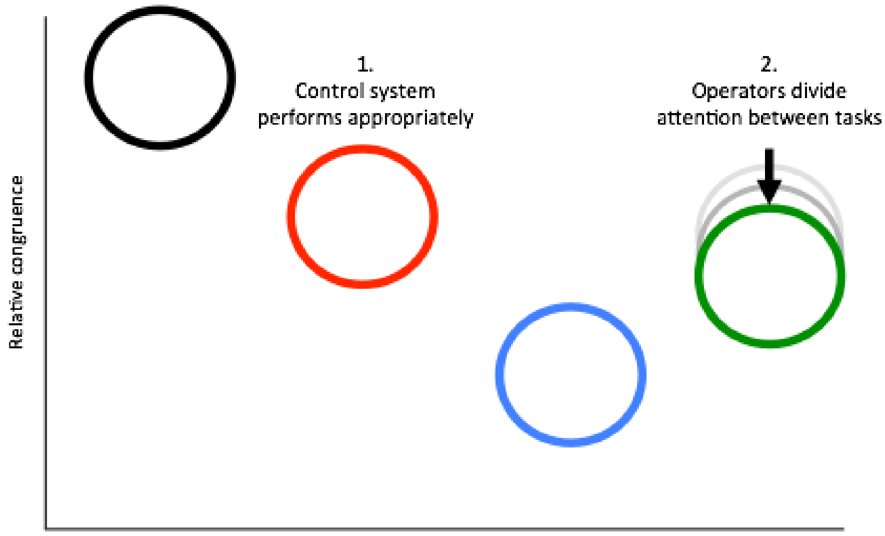


Figure 14. Out-of-the-loop (II)

In out-of-the-loop (II) the control system works so reliably that the operator can spend time and attention on other tasks (Figure 14). In the transition from normal state to an out-of-the-loop (II) problem, the trade-off between monitoring automation and getting other things done may cause a deterioration of the operator’s mental models. In the case of an adverse event with the automatic control system, operators will have to work themselves back into the loop and regain understanding in order to close the gap.

Andersson and Osvalder (Andersson and Osvalder, 2009; Andersson, 2008) found examples of out-of-the-loop (I) problems in turbine operation presented in a study of an automatic turbine system performed in a full scope nuclear power plant simulator. Operators reported it was difficult and time consuming to manage anomalies and find the root cause of a failure in the automatic turbine system. Trouble shooting activities would have been easier if the actions preceding the anomaly had been performed manually, where appropriate feedback was present. The cause attributed to the difficulties was the difference in feedback from the automatic turbine system panel, compared to feedback when performing actions manually.

In the same study (Andersson, 2008), out-of-the-loop (II) was found to be a natural consequence of using higher levels of automation. When using the turbine automation interface instead of acting manually on the interface of specific process equipment, the operators found themselves less aware of what equipment had been engaged. When using step-wise automation sequences, operators could control the pace of operations, and the combination of effective task automation and time to manually check was perceived as an effective way of working.

2.6.3 Loss of skills and knowledge

In the context of automation problems, loss of skills can be defined as the deterioration of manual and cognitive skills and knowledge due to the use of automatic control systems that reduce the possibility of practicing manual tasks. Thereby, the control system interface has to provide additional support to enable the operator to remember and perform tasks despite lack of manual practice.

Loss of skills and knowledge occurs as a result of operators not being able to perform manually the tasks that have been automated. This leads to deterioration of physical task performance skills. The operator's mental representation may also fade when not regularly used and maintained, thus loosing cognitive skills (Bainbridge, 1983).
It is worth noting that loss of skills and the out-of-the-loop problem are dependent on each other, since loss of skills worsens the out-of-the-loop problem when understanding of the controlled dynamic domain is reduced. Also, the out-of-the-loop problem may cause loss of skills over time, as the operator is not engaged in active control (Lee, 2006). For example, Andersson and Osvalder (Andersson and Osvalder, 2009; Andersson, 2008) found that infrequent use of control system functions in turbine automation operation caused insecurity when operators needed to perform critical actions in live situations.

The nature of the required skills can be changed when a control system is introduced as an intermediary between operator and technical system. An increased level of automation means that manual actions are replaced by monitoring tasks, which could increase rather than relieve demands imposed on the operator (Bainbridge, 1983).

Degradation of skills and knowledge represented as model incongruence

Skill degradation results when a control system takes over functions and the operator has no need to practice functions manually. Operator skills and knowledge (i.e. the mental model of the work domain) deteriorate as a result of lack of practice. If the control system fails at a later point in time, the knowledge needed by the operator to handle the situation has faded. Loss of skills is of a similar pattern to out-of-the-loop (II) (Figure 14), where the operators' mental model degrades due to lack of practice.

Andersson (2008) found examples of loss of skills in a study of nuclear turbine operation. Degradation of skills led to insecurity in operators when asked to operate equipment rarely used. In the nuclear domain, loss of skills is actively prevented by annual simulator training. However, during simulator training, the focus is mainly on safety-critical events, which in this case left seldom performed, yet normal, activities unpractised.

2.6.4 Miscalibrated trust of control systems - complacency, distrust and eutactic behaviour

The concept of trust in automation is used to describe to what extent an operator relies on an automatic control system. Operators can rely on the control system to different extents and reliance can vary over continuous grades, rather than being a static binary state of either too much or too little reliance (Lee and See, 2004).

Overreliance or complacency is created as operators form beliefs that the technical system is more competent than it actually is (Lee, 2006). On the other hand, operators can also come to form a sceptical view of the technology, and hence attribute too little competency to the technical system. This is referred to as distrust (Parasuraman and Riley, 1997).

Eutactic behaviour is a term used to describe when an operator has appropriate reliance that could be inconsistent with the expectations of designers and managers (Moray, 2003). The operator might perform supervisory control in such a way that sampling frequency, when monitoring, is consistent with the probability of failure. However, since failures in automatic systems occur seldom, the distance in time between each sample is long, thus leading to a risk of failures being missed, although the operators perform statistically correctly. Operator behaviour is often based on trade-off between benefit of having time to perform other tasks (and directing attention elsewhere) versus value of detecting failures and deviations. Monitoring the control system closely may not be worth the effort, since deviations happen very seldom. However, the operator risks being blamed for inappropriate monitoring, despite a statistically appropriate monitoring behaviour.

If operator trust fails to match with control system capabilities, problems with misuse and disuse can occur (Parasuraman and Riley, 1997). If the operator does not trust the control system to perform appropriately, higher levels of automation are likely to be abandoned and the advantages of the automatic system may be lost and economic benefits reduced. Complacency on the other hand, can cause the operator to fail to notice when the control system does not perform as intended.

Operators can exhibit varying degrees of functional and temporal specificity in relation to trust (Lee and See, 2004). High functional specificity refers to how trust is attributed to a specific part or subsystem capability, whereas low functional specificity may refer to the system as a whole (Figure 15). Temporal specificity describes how trust changes over time – for example how the operator manages to adjust trust if an automatic function fails repeatedly. Low temporal specificity indicates how operator calibration of trust lags behind and changes too slowly. High temporal specificity indicates when the operator changes conception of trust optimally, i.e. continuously reconsiders whether or not an automatic system performs reliably.

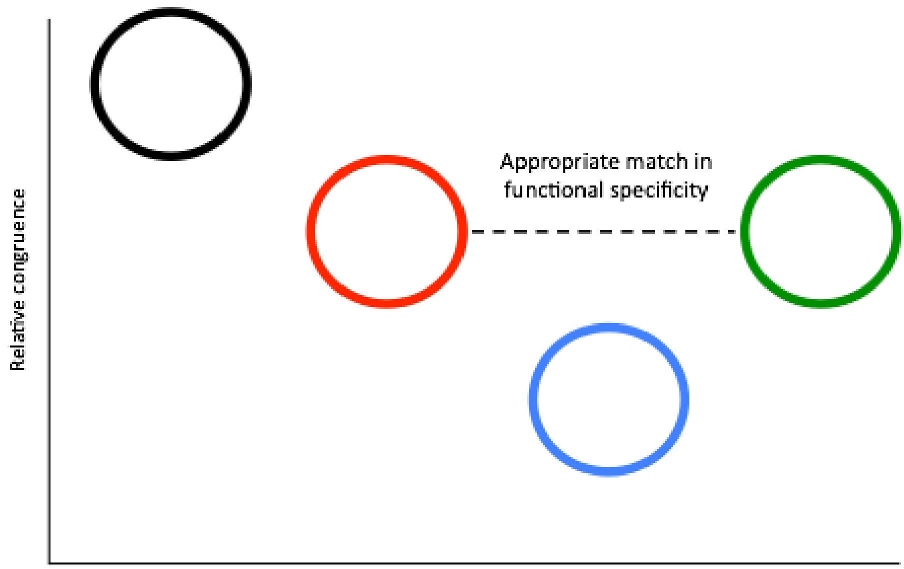


Figure 15. High functional specificity

A number of factors affect operator reliance. Primarily, a high reliance is formed as a result of adequate control system performance. Operators will come to trust technology that seldom fails, and to be sceptical towards technology that often fails to perform as intended (Moray and Inagaki, 2000). Trust is also affected by for example, the operator's self-confidence, perceived risk, interface features, the control system's reputation etc. (Finger and Bisantz, 2002). To summarise, trust is a multi-faceted aspect of human-machine interaction that may lead to a number of unwanted outcomes.

Miscalibrated trust represented as model incongruence

Miscalibrated trust can occur either as distrust or complacency. Distrust emerges when the operator believes the control system to be less reliant than it really is (Figure 16). Inappropriate reliance can cause distrust and disuse, failing to appreciate the full functionality of the control system.

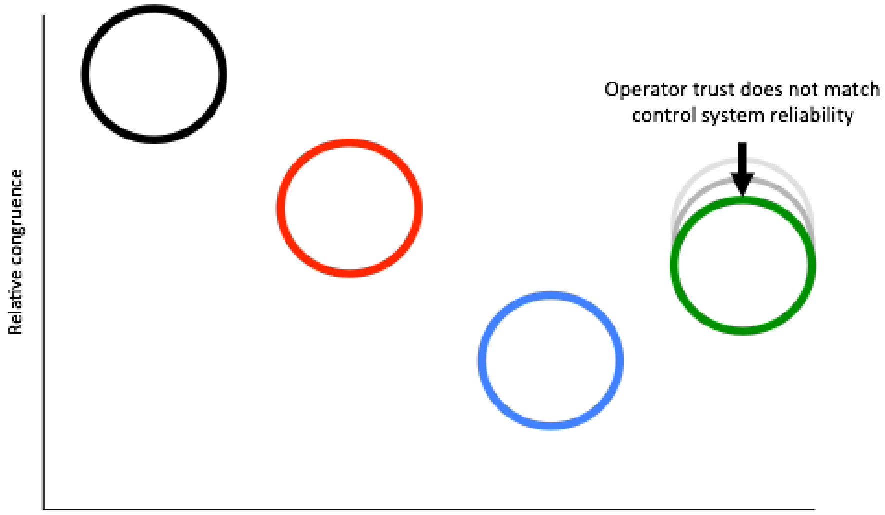


Figure 16. Miscalibrated trust

In the triadic representation, mistrust can be depicted as a mismatch between the operator and the control system. The operator does not have an accurate model of how the control system works, which can lead to inappropriate reliance. By studying the relations between the parts as represented in Figure 11, the build-up and deterioration of trust can be elucidated. For example, if an operator never gets the chance to perform any exploratory actions, the boundaries that the control system acts within might never be discovered. By allowing the operator to test hypotheses of control system reliability, trust calibration could be facilitated. Opaque control systems, where the working mechanisms are unobservable, will make it difficult for operators to understand when automatic functions might behave unreliably in relation to their expectations. Representing uncertainties in the user interface (see Finger and Bisantz, 2002 for examples) is an attempt to provide the operator with information about reliability in order to reduce the gap between operator and the perceived control system reliability.

Complacency

The opposite of distrust, called complacency, refers to when the operator trusts the control system too much. The operator believes that the control system is more competent than it really is. This leads to the operator putting more trust in the control system than is appropriate.

Complacency occurs as a result of operator's model of the control system failing to match the capabilities of the control system. Complacency emerges in the relation between operator and control system, but can also be an effect of changes in the dynamic domain state. For example, if the state changes to a situation where the control system moves outside its normal operating range, complacency can occur if the operator believes the control system still works as it has done before.

Eutactic behaviour represented as model incongruence

Eutactic behaviour is when the operator monitors the control system in accordance with the probability that a failure will occur. Highly reliable control systems will then statistically need less supervision. Infrequent monitoring will however, increase the probability of missing signs of anomalies undetected by the alarm system.

No empirical examples of trust calibration have been investigated in my own studies. However, the paint factory simulator can be used to create a hypothetical example (see section 5.5 for a description of the simulator). If the operator does not trust the control system sequence program to perform dosing correctly for example, due to repeated erroneous batches, the operator can choose to perform the dosing manually. However, a bad batch is not necessarily a result of a malfunctioning control system; it can be due to e.g. poor quality in the pigment's raw material. Miscalibrated trust can thus occur as an effect of the operator having an incongruent domain model, where the choice not to use automatic functions will lead to loss of efficiency in production.

2.6.5 Automation induced errors

Automation induced errors refers to the types of errors occurring as a result of increasing the level of automation. One reason often used as a motivation to increase the level of automation is to reduce human error. However, new types of errors have been shown to occur as a result. Two examples of these problems are brittle failures, and configuration errors.

Brittle failures

Brittle failures refer to when automation causes a sudden degradation of human-automation system performance. This can happen if the control system compensates for failures which then may go unnoticed by the operator. When the control system can no longer accomplish compensation due to work domain constraints, over-all performance may degrade suddenly. This is in contrast to the often graceful degradation in manual work, where performance degrades more slowly over time and can thus be easily detected.

Brittle failures refer to how the control system can compensate for a failure in the domain and thereby mask system degradation. When the control system can no longer compensate, the system performance degrades suddenly. In the transition from normal performance to brittle degradation, the system moves through two phases. First, the control system compensates, which may obscure the system state if the user interface only shows the performance of the dynamic domain, and not how the control system struggles to compensate for a failure. Due to the user interface inability to represent the control system, the operator's model of what is happening is also degraded. Next, when the problem moves outside the control system's operating range and the control system no longer can compensate for the failure in the dynamic domain, the system performance fails abruptly.

A typical example of a brittle failure is a water leak compensated by the control system increasing the flow. If the leak increases, the control system can compensate within the pumps operating range, which could mask the leak by keeping the observable tank level constant. If the user interface presents tank levels and flow, but not how the control system continuously adjusts pump activity, early detection of the failure will be obstructed.

Representing brittleness as model incongruence

Brittleness occurs when the control system compensates for dynamic domain deviations as long as it can, thus hiding the anomaly from the operator. When the control system fails to withhold the deviation and it reaches its boundary condition, the anomaly will reveal itself as a far worse situation than if it had been detected from the beginning, often resulting in rapid degradation of system performance. The behaviour is brittle, since the system appears to "crack" rapidly, rather than degrade gracefully.

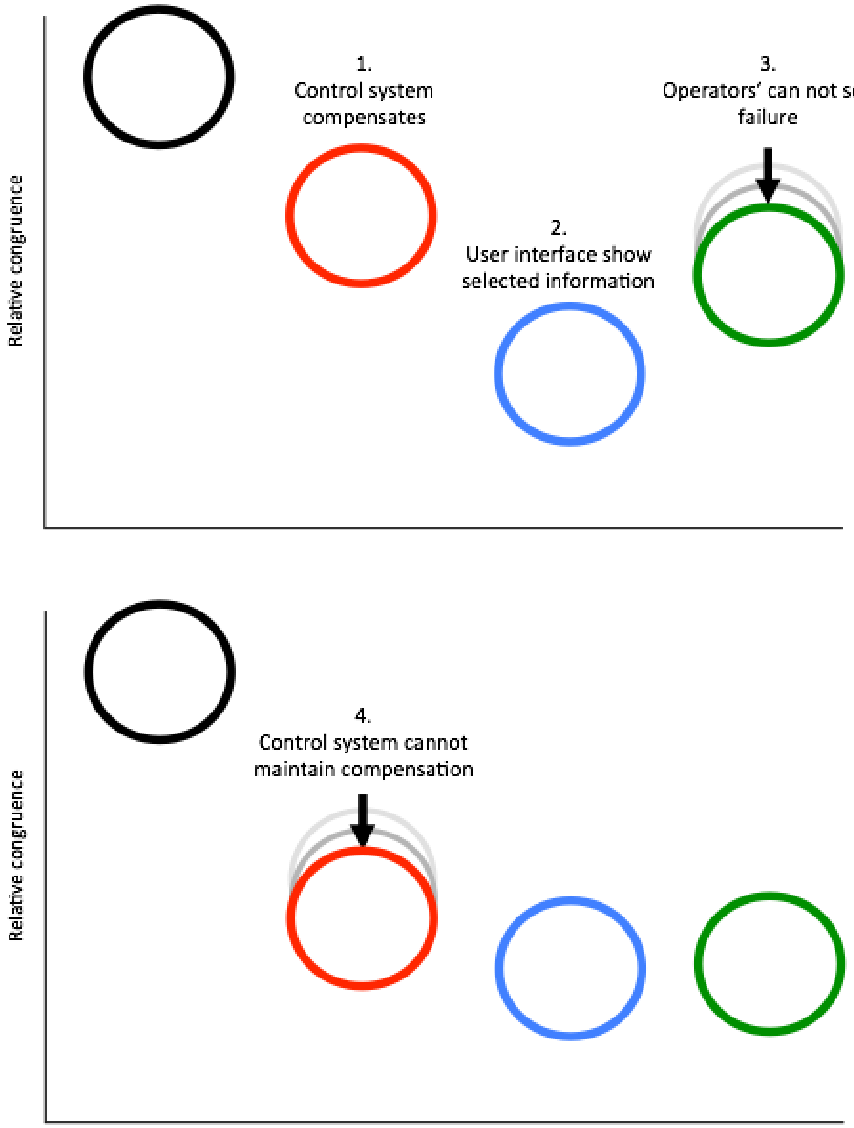


Figure 17. Brittleness

In this case the dynamic domain state is held stable, while the control system will exhibit variations when it compensates for an external deviation (1). If the control system's effort to withhold dynamic domain stability is not communicated (2) to the operator everything will appear normal (3) until the control system is unable to compensate (4) and the dynamic domain will deviate rapidly.

Configuration errors
In advanced automated human-machine systems, the control system can be configured to handle tasks in a specified way. For example, in the maritime domain the navigation system can be directed to keep to a specific course and warn the crew should the ship sail too close to another vessel. If the wrong margins are unintentionally entered the ship could sail too close to other sea traffic, especially if the automatic navigation system is heavily relied upon. Thereby, a configuration error can jeopardise safety. The same thing is applicable in aviation, where the flight management system can be accidently fed with incorrect data, which could take the pilot unawares and compromise safety.

Representing configuration errors as model incongruence
Configuration errors occur when operators feed incorrect information into the control system (1). The operator builds the expectation of how the dynamic domain will respond to the input, the control system will act correctly based on the input, but this will not be in the way expected (2). Wrongly configured, the control system can react in unexpected ways and take people by surprise. (3).

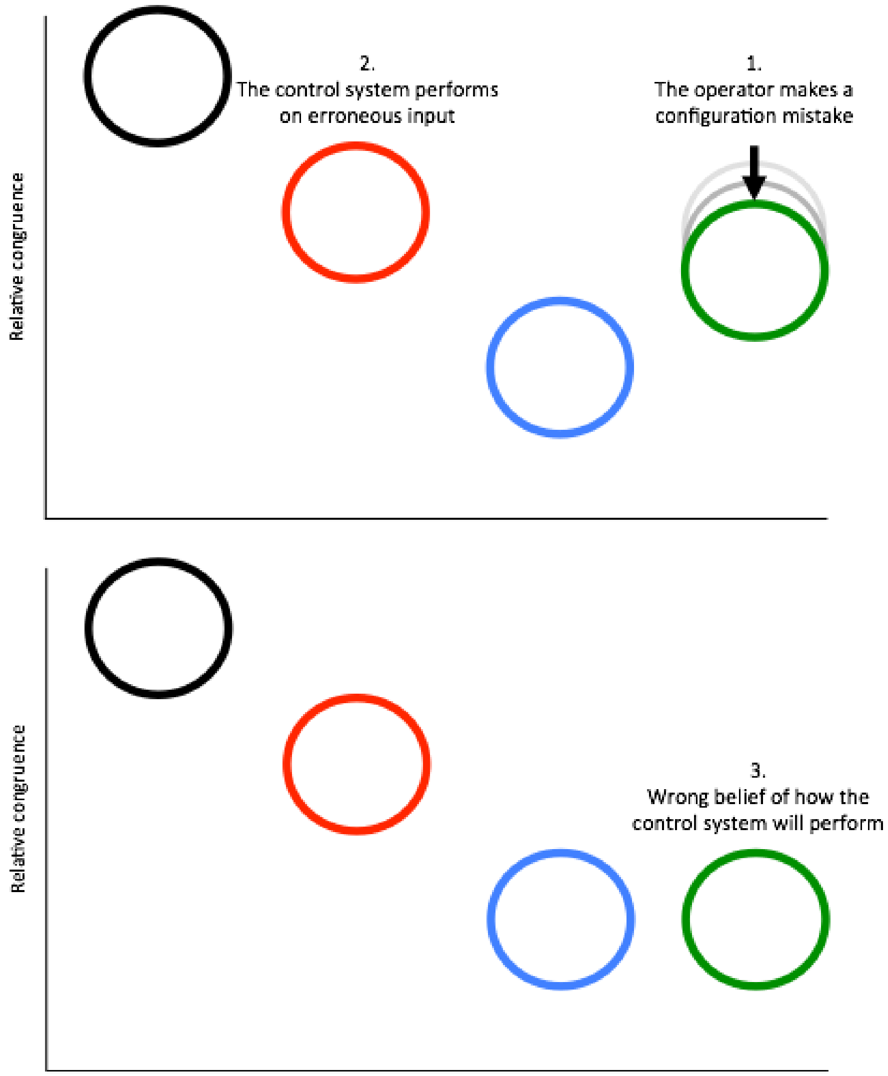


Figure 18. Configuration error

The control systems instruct the process equipment to adapt to the new information but, if a configuration error has occurred, the dynamic domain variation will not be what the operator expects. Due to time delays and sluggish process change, the configuration error may go unnoticed for a long time, which makes it difficult to detect. In the transition period from error made to problem arising, the operator's input error will cause a mismatch between the operator's model of how the control system and dynamic will behave and what will actually happen. The mismatch can remain latent for a long time before the error results in an observable change in the dynamic domain. The detection of the change will then decrease the mismatch again.

Configuration errors typically happen when the operator is in the teaching role, giving input to the control system. The error can happen as a misreading of a procedure or a typo. If the control system does not sense the normal or intended range of input in the situation, the error can pass unnoticed.

An example of configuration error was found in the control room evaluation experiments performed using the paint factory simulator (Osvalder et al., 2013), used as a case example in chapter 1. In the paint factory simulator, the input of the wrong recipe parameters can lead to quality disturbances or a need to drain a whole paint production batch. The error can be difficult to detect after the batch has been started and attention is directed elsewhere. The paint factory control system features protection against over filling the tanks, meaning it is not possible to input more material than the tank can contain (10 000 kg). This precaution prevents flooding of the tank, but does not hinder input of the wrong batch recipe, since the recipes varies greatly depending on colour, paint quality and batch size.

2.6.6 Mode awareness and automation surprises

Mode awareness is the ability of a supervisor to track and anticipate the behaviour of an automatic system (Sarter et al., 1997). This has similarities with the out-of-the-loop problem. Since automated human-machine systems can change their mode of operation based on environmental or contextual input from sensors and coupled systems, it can be difficult to track and understand the actions of a technical system that seemingly acts on its own. This behaviour may lead to 'automation surprises' that may compromise safety and operational performance.

For example, Sarter and Woods (2000) showed how pilots of the advanced Airbus A-320 experienced surprises as the aircraft acted unexpectedly in various situations. Some findings could be related to high autonomy but low observability of flight computer actions and intentions.

Another example is given by Lützhöft and Dekker (2002) in their analysis of the grounding of the passenger ship Royal Majesty. In this example, the crew remained unaware of the GPS signal being lost for several hours. The ship was navigating in dead reckoning mode and ran aground 10 miles east of Nantucket Island. However, the cause of grounding cannot be attributed to the single cause of a lost GPS signal but, as Lützhöft and Dekker made clear, the path of events were dependent on contextual, organisational, team, individual and technical factors all contributing to an escalating situation.

Representing mode confusion as model incongruence

Mode confusion refers to when the operator believes the control system is in another state than it is. Given a specific dynamic domain state, actions can give unexpected results, since the control system will act on a functional premise that differs from the operator's belief.

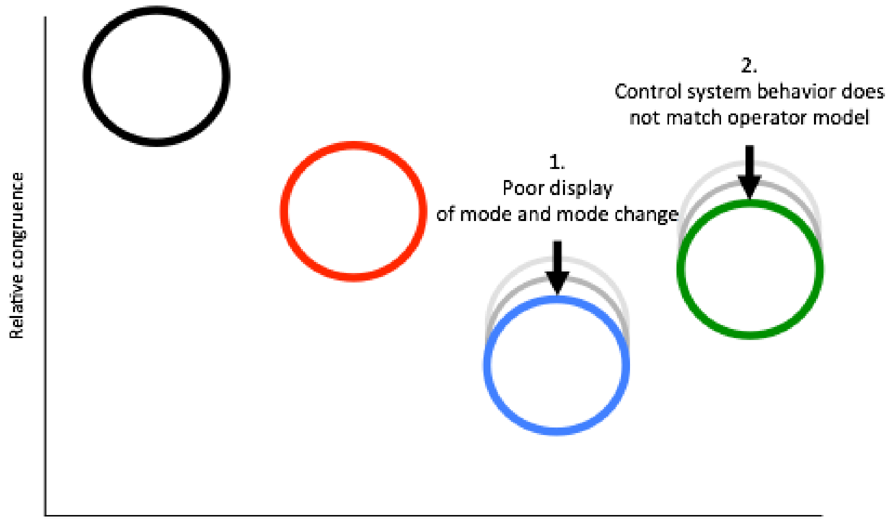


Figure 19. Mode confusion

Figure 19 shows how mode confusion stems from the control system being in another state than expected by the operator (1). The operator's model of how the control system will react and change the dynamic domain does not match the actual system state (2).

Representing automation surprises as model incongruence

Automation surprises are closely related to out-of-the-loop, brittleness, and mode awareness. If a system fails abruptly in a brittle way, it can lead to surprise. Surprise occurs when the operator is unable to foresee how the system will behave. If the operator is unable to see or understand what the control system is doing and how it affects the dynamic domain, it will be difficult to maintain a corresponding model of what is going on. Surprise occurs when one thing is expected and something else occurs. When the system changes into a state where the operator's model does not correspond to the system behaviour, surprises can occur unless the operator knows that the model is inadequate i.e. expects variation. If the operator expects variation, the operator can prepare to explore and learn in the face of changing operating conditions. Automation surprises can be described as the result of the pattern in Figure 13, Figure 14, Figure 17 and Figure 19, but the surprise occurs as the first phase of detecting that the situation has gone awry. The green operator circle will then start to close in on the dynamic domain as the operator realizes that something is wrong.

In a study of nuclear power plant turbine operation, Andersson (2008) found an example of how poor control system interface transparency can cause surprising events. In this case the interface did not aid the updating of the operator's working model regarding existing preconditions for initiation of automatic sequences. One operator referred to the situation as "being caught with your pants down", when having caused a turbine scram due to a missed precondition during initiation of an automatic sequence.

2.6.7 Summary of automation related problems

In the preceding sections, automation related problems have been described from a new perspective, namely incongruent variation. Variation within the dynamic domain-control system-operator triad implies that something within the circles has changed to another state. As recently presented, automation related problems can be described in terms of variations that happen in some parts of a system, but where corresponding parts are left behind. To avoid incongruence, variations have to propagate across the human-machine system to all corresponding parts. Without correspondence between parts, incongruence will emerge as an effect of inability or sluggishness in the adaptive capacity of the human-machine system.

Next we will look at what affects model incongruence and how existing prescribed solutions and design guidelines correspond to the concept of incongruent variation between models.

2.7 Prescribed solutions to automation related challenges

A number of academic publications prescribe generic theoretical recommendations to resolve automation related problems (Bainbridge, 1983; Dekker and Woods, 2002; Endsley et al., 2003; Klein et al., 2004; Lee, 2011; O'Hara and Higgins, 2010; Sarter et al., 1997; Woods and Hollnagel, 2006; Woods and Sarter, 2000; Woods et al., 2002). In the following sections three references (Endsley et al., 2003; O'Hara and Higgins, 2010; Woods and Hollnagel, 2006) have been chosen as examples of recommendations. Woods and Endsley were chosen since they represent two contrasting theoretical perspectives (joint cognitive systems and situation awareness). O'Hara and Higgins were chosen since their compilation of recommendations cover many key references and are up-to-date.

2.7.1 Supporting human-control system team play

For example; Woods and Hollnagel (2006) suggest four generic requirements to support ”joint cognitive systems that work”, which include human-control system team play: Support for Observability, Support for Directability, Support for Directed Attention and Support for Shifting Perspectives. In short, Support for Observability means feedback that provides insight to a dynamic domain. Support for Directability means ability to direct and re-direct resources as situations change. Support for Directing Attention is important when focus has to be changed to an issue of higher importance in a dynamically changing environment. Support for Shifting Perspectives will facilitate seeing alternative points of view and other possible solutions.

Supporting Observability and providing an insight relates to both the operator's controller and the observer function (see section 2.3). The operator and control system actions that produce a response must be visible for the operator to detect deviations and to test beliefs and hypotheses. Providing observability means that representations of the dynamic domain and the control system should support the operator in making the automatic behaviour predictable. To aid observability, the control system should model the dynamic domain sensitively enough to perceive relevant events (gap A). If the control system cannot perceive the system dynamics sufficiently well (e.g. due to too few sensors or low sample frequency) the information delivered to the control system user interface may be insufficient for detection of anomalies (gap B), i.e. the operator will suffer from the out-of-the-loop I problem (Figure 13). The control system user interface should mirror the dynamic domain (gap C), so that the dynamic domain can be observed and understood. Understanding depends on the operator's own model of the control system (gap D) and the dynamic domain (gap F). For the information in the control system user interface to be distinguishable, the interface must be designed in accordance with human perceptual abilities, which means the user interface will incorporate a model of the operator[2] (gap E).

Support for Directability is supported by the ability of the control system to control the dynamic domain (gap A) and means for the operator to take action (gap B). To know where to direct, the operator is naturally dependant on feedback functions from the control system (gap B and C).

To re-direct Attention, the operator will benefit from knowing the possible and expected outcomes in a given situation. For example, models of the dynamic domain and control system (gap D and F). Also, the control system model of the operator (gap E) plays a role in attracting attention, e.g. how should, for example, an alarm system be designed for a human operator to rapidly perceive, differentiate and understand an alarm signal. The challenge is however, to detect and diagnose unexpected events, often inflicted by unimaginable events outside the work system. These adverse events stress the necessity of a developed operator model of the dynamic domain and the control system (gap D and F) to facilitate reassessment of how the system will behave if some functions are lost.

Shifting Perspectives rely on supporting the operator's observer function. Through the observer function the operator can challenge current beliefs and falsify own hypotheses. Since taking one perspective will obscure another view (Hoffman and Woods, 2011), the control system user interface must provide multiple information sources that can be combined to shed light on issues from different angles (gap A). The user interface is dependent on upstream information sources and on the control system's ability to collect relevant measurements (gap B). The ability to come up with new ideas and take another stance depends on the operator teams' collective ingenuity and knowledge of the dynamic domain and control system (gap D and F). Operators will also have knowledge, e.g. experiences from other domains, that can spur new ideas for solutions.

2.7.2 Supporting situation awareness

The situation awareness concept is relevant to supervisory control, since it is concerned with, as Endsley (2003) states: "... being aware of what is happening around you and understanding what that information means to you now and in the future". There are a number of different theories of situation awareness (e.g. Artman, 2000; Endsley, 1995; Flach, 1995; Shu and Furuta, 2005; Smith and Hancock, 1995). Despite the differences, all theories share the common elements that people perceive information from the situation, make a representation (mental model) of that situation, make predictions of the future based on the representation and make decisions and act to reach a given goal (Westrenen and Praetorius, 2012). According to Endsley et al (2003), situation awareness can be divided into three levels. Supporting Level 1 means aiding perception of elements in the current situation, supporting Level 2 aids the comprehension of the current situation and Level 3 means supporting the projection of future status. To support situation awareness in automated systems, Endsley (2003) prescribes eleven principles for design. Below, the principles are related and interpreted in terms of the model presented in Figure 11.

[2] By designing technical artefacts so that they match human capabilities, the artefact will mirror the human (i.e. making use of perceived affordances) An example is the way a handgrip incorporates a model of a human hand.

Principle 1: Automate only if necessary, since automation increases complexity and complexity makes system understanding more difficult

Introducing more complexity to the control system affects gap A, B and D. Gap A will shrink as the control system models the controlled dynamic domain more accurately. Gap B will increase unless the control system interface is adapted to reflect the control system change in an understandable way. Gap D will increase, since control system understanding becomes more difficult for the operator.

Principle 2: Use automation as assistance for carrying out routine actions rather than higher level cognitive tasks

In general, physical actions are easier to observe than cognitive tasks. If the control system performs routine actions, it is easier for the operator to perceive and understand the basis for action compared to a control system action that is preceded by an advanced cognitive task. The operator's comprehension depends on the understanding of the control system (gap D) and how the control system acts in the dynamic domain (gap A).

Principle 3: Provide situation awareness support rather than decisions, because automated decision making tends to impose decision biases

To support perception (Level 1 situation awareness) relates directly to how well the control system can mirror the dynamic domain (gap A) and how this image is depicted in the control system user interface (gap B). Supporting comprehension (Level 2 situation awareness) of current situation relates to how well the dynamic domain and the control system is understood, i.e. how well the operator's model matches the dynamic domain and control system (gap A and B). The projection of future status (Level 3 situation awareness) is based on drawing conclusions from earlier experiences (conceptual model) (gap D and F) in combination with perception of the current status (gap C).

Principle 4: Keep the operator in control and in the loop to enhance operator abilities to detect and understand problems

To keep the operator in control the operator needs the ability to carry out performatory actions and detect the consequences to see if the error has been reduced. But being in the loop also implies that the operator can check if their current beliefs are true, i.e. using exploratory actions as a means of investigating the state of the system and comparing it to the mental model.

The generic recommendation to enhance the ability to detect and understand problems is related to many of the gaps in Figure 11. To support detection of problems in the dynamic domain depends on how the dynamic domain is measured (gap A) and how the dynamic domain is represented in the control system user interface (gap C). Detection of problems in the control system depends on how the control system user interface represents the inner workings of control logic and functionality (gap B). Operator understanding depends mainly on operator knowledge of the dynamic domain and control system (gap F and D), but also on how the control system can represent the dynamic domain and the control system (gap B and C). Finally, operator possibility to detect and understand depends to some extent on the control system user interface model of how the operator perceives information (gap E). In other words, user interface affordance will determine how information from the control system user interface will be received by the operator.

Principle 5: Avoid the proliferation of control system modes because more modes and function branches increase complexity

Avoiding too many modes will make it easier for the operator to keep track of modes and functions, which could help reduce mode awareness problems, since excess complexity is reduced. The gap between the control system and the control system user interface (gap B), and between the control system and the operator model (gap D), will be easier to reduce with fewer modes and functions. Proliferation of modes could however, be motivated in order to improve control system match to the dynamic domain (gap A), but in that case other models would have to be adapted to (at least) avoid increased mismatch.

Principle 6: Make modes and system states salient so that it is made clear what mode the system is in

Making modes and system states salient will mean a reduction of the gap between the control system user interface and the control system (gap B), as the user interface will better reflect the control system and the dynamics of the domain. According to the model in Figure 11, the gap between the control system user interface and the operator (gap E) would also be affected. Gap E is reduced with appropriate salience, since the control system user interface will then contain a better model of how the operator perceives information and how to attract the operator's attention. The design challenge is to know <u>when</u> to attract attention and <u>how</u> to design the signal (how loud, how bright, etc.). The gap between the dynamic domain and the control system user interface (gap C) is not necessarily affected by making modes and system states salient, as gap C reflects the information content of the user interface, rather than how it is designed to match the operator's cognition.

Principle 7: Enforce control system consistency to make automatic functions work similarly across modes

Consistency of the control system is a property that will affect the gap between the control system and the operator (gap D) because consistency will facilitate the operation of the control system and potentially reduce the probability of mode errors.

Principle 8: Avoid advanced queuing of tasks when consequences of failure are high because it makes it difficult for the operator to track what's going on

If the conditions in the dynamic domain change over time without being recognised by the control system, queued actions might lead to other consequences than intended. Endsley reports that such use of advanced queuing caused out-of-loop symptoms in pilots. Instead, keeping the operator engaged e.g. by confirming decisions before they are implemented, could avoid the problem. In terms of the model in Figure 11, keeping the operator in the loop would mean that the gap between the control system and the operator is reduced by making the operator actively participate in control system activities.

Principle 9: Avoid the use of information cueing because if the model for cueing is wrong it might lead to confusion

Information cueing, i.e. pointing out to operators where to direct their attention, means that the control system highlights areas of interest that are shown in the control system user interface. If the control system's model of the dynamic domain is wrong (gap A), then the incorrect guidance to the operator through the user interface (gap C) can lead to operators looking for information in the wrong places, which would prevent understanding (gap F).

Principle 10: Use methods for decision support that create human/system symbiosis

Endsley presents three alternate approaches to decision support that would improve human/system symbiosis:

- Supporting what-if analysis and encouraging people to consider multiple possibilities and perform contingency planning, which would aid formulation of Level 3 situation awareness,
- Systems that help people consider alternative interpretations of data,
- Systems that directly support situation awareness by directly calculating Level 2 situation awareness requirements and Level 3 situation awareness projections.

Approach (i) and (ii) are both related to how well the dynamic domain and the control system are represented by the control system user interface (gap B and C). If the control system user interface can reflect and represent the complexity of the dynamic domain and the control system, it will be possible to see the world from more than one perspective. To take another view however, also depends on the capability of asking the right questions, which depends more on the operator's knowledge of the control system and the dynamic domain (gap D and F). To visualise information to facilitate a new interpretation also demands flexibility of the available information systems. For a long time, many control system user interfaces in process industries have only showed the physical structure and process values, without reflecting inherent functional interdependencies and domain constraints. With new capabilities in digital technology, emerging solutions however, make use of the large amount of data available in the many different information systems running in a plant (Clark and Turk, 2013; Hollender, 2010; Thoresson, 2010). Together with flexible visualisation tools, this can facilitate the formation of new perspectives to improve understanding.

Approach (iii), aiding comprehension of the current situation (Level 2 situation awareness) and supporting projections (Level 3 situation awareness) are determined by several gaps in Figure 11. Firstly, comprehension is dependent on the operator's conceptual model of the dynamic domain (gap F) and the control system (gap D). Comprehension is supported by the control system user interface in how it manages to adapt the operator's short term mental model (gap E) to match the current dynamic domain state (gap F). The quality of comprehension aiding depends on how well the control system user interface can reflect what is happening in the dynamic domain (gap C) in a way that can be grasped quickly by the operator (gap E). The control system user interface is in turn, dependent on the information of the dynamic domain that can be delivered from the control system (gap A), and how the information is represented (gap B). Secondly, the ability to project future events relies on the ability to see dynamic domain behaviour over time and be proactive. This requires a thorough conceptual model of the dynamic domain and control system (gap D and F), which enables mental simulation. The control system user interface can be of great help in seeing events over time (e.g. producing trend curves), which directly aids projection (although non-linear dynamics can be difficult to assess). Given the dynamic character of a specific process value (e.g. linear, exponential, etc.), the control system model can aid projection, within the limitations of the control system's model of the dynamic domain (gap A).

Principle 11: Provide control system transparency

The transparency guideline provided is directly related to the main idea of representing model mismatch as gaps in Figure 11. As was stated earlier, the model gaps in the system can never be completely eradicated. However, if design solutions can help reduce the gaps in Figure 11, system transparency has a better chance of being enhanced, since the operator will have the knowledge (gap D and F) and the means (gap A, B C and E) to adapt to changing conditions.

2.7.3 Principles for supporting teamwork with machine agents

The US Nuclear Regulatory Commission (O’Hara and Higgins, 2010) provides a summary of important aspects to support human-control system co-agency in the nuclear domain. The principles are gathered from several supervisory control domains and include nine general principles for supporting human-control system teamwork. The main part of the summary is presented in Table 5.

Table 5. Nine general principles for supporting teamwork with machine agents. Cited from O'Hara and Higgins (2010)

Nine general principles for supporting teamwork with machine agents	
Define the purpose of automation	Automation should have a clear purpose, meet an operational need, be well integrated into overall work practices, and be sufficiently flexible to handle anticipated situational variations.
Establish locus of authority	In general, personnel should be in charge of the automation, be able to redirect, be able to stop it, and assume control, if necessary. [...] Some actions are allocated to automation because they cannot be reliably performed by personnel within time- or performance-requirements. There may be situations where automation initiates a critical action because personnel have failed to do so. [...]
• Optimise performance of the human-machine team	The allocation of responsibilities between humans and machine agents should seek to optimize overall integrated team-performance. [...] Personnel’s interactions with automation should support their development of a good understanding of the automation, and the maintenance of their personal skills needed to perform tasks if automation fails. [...] The HSIs should support a clear mutual understanding of the roles and responsibilities for both human and machine agents.
• Understand the automation	Personnel should clearly understand the automation’s abilities, limitations, and goals, and be able to predict its actions within various contexts. [...] the HSI should accurately represent how the automation functions overall, and how it interacts with the plant functions, systems, and components.
• Trust the automation	Personnel should have a well-calibrated trust in automation that involves knowing the situations when the automation can be relied on, those which require increased oversight by personnel, and those which are not appropriate for automation. The HSIs should support the calibration of trust, such as providing information about the automation’s reliability in its various contexts of use and specific functions.
• Maintain situation awareness	The HSIs to automation should provide sufficient information for personnel to monitor and maintain awareness of automation’s goals, current status, progress, processes (logic/algorithms, reasoning bases), difficulties, and the responsibilities of all agents. [...]

Nine general principles for supporting teamwork with machine agents	
• Support interaction and control	Personnel interaction with automation should support the human's supervisory role: - HSIs should support personnel interaction with automation at a level commensurate with the automation's characterisation, e.g., level, function, flexibility, and its reliability. - Communication features should enable personnel to access additional information about automation's processes beyond that provided in monitoring displays. [...] - Personnel should be able to redirect automation to achieve operational goals. [...]
• Minimise workload from secondary tasks	A minimal workload should be entailed in dealing with the automation's configuration, and in monitoring, communicating, changing allocations, and directing it.
Manage failures	Automatic systems should support error tolerance and managing failures: • Personnel should monitor the activities of automation to detect automation errors, and be adequately informed and knowledgeable to assume control if automation fails. • Automation displays should support operators in determining the locus of failures as being either the automation, or the systems with which the automation interfaces. • To the extent possible, automation should monitor personnel activities to minimise human error by informing personnel of potential error-likely situations. • Automation should degrade safely and straightforwardly when situations change sufficiently to render its performance unreliable, and should communicate this to personnel in a timely way [...].

Define the purpose of automation

In the process industry, the general rational for automating a plant section is economical (Hollender, 2010). Therefore one of the main purposes of a control system is to reduce cost through for example, improved quality and enhanced safety. For a control system to be sufficiently flexible to handle anticipated situational variations, the control system will benefit from having a sufficiently accurate model of the dynamic domain (gap A). At the same time, operations benefit from keeping the control loops as simple as possible, because this goes hand in hand with accurate understanding.

Establish locus of authority

The locus of control is determined by the relation between the control system and the operators in different situations, and the opportunities to divide control is set by the control system designer. The locus of control will be different across situations and for different control system functions. For the operator to understand when the control allocation will change, the triggering mechanisms must be clear (gap A and D) and communicated through the user interface (gap B).

Optimise performance of the human-machine team

The idea of the model in Figure 11 is that by working to minimise the gaps and strengthen congruence between models (gaps A-F) in the work system, this will improve the performance of the human-machine team in terms of avoiding automation related problems. The design challenge for human factors engineers then consists of creating representations (e.g. for operation and training) of the dynamic domain and the control system that will aid the operators' understanding of dynamics and complexity inherent in the work system.

Understand the automation

Understanding the control system is dependent on how the control system user interface manages to communicate the inner workings of the control system (gap B). Understanding also depends on the operator's own model of the control system (gap D).

Trust the automation

Trust is developed when the control system behaves as expected, i.e. according to the operator's model. Hence trust is affected by gap D. According to O'Hara and Higgins (2010) the control system's reliability should be communicated, which also make calibration of trust related to gap B.

Maintain situation awareness

For an examination of how the model in Figure 11 is related to situation awareness please see '*Supporting situation awareness*' section (2.7.2).

Support interaction and control

Support of the supervisory role requires support of the operator's controller and observer function (Figure 8). 'Commensurate' interaction requires the representation of the level, function, flexibility and reliability in the control system user interface to reflect how the control system is built and how it works (gaps A to F). Information from sub-systems that are controlled from elsewhere, but have an impact on the controlled dynamic domain, should be easily accessible, since unexpected activities in related parts of the plant can propagate in a factory where subsystems are tightly coupled (e.g. subsystems or parts of a plant that use the same resources but are controlled from different locations). Information that might be inaccessible from the control system user interface could be activities in related parts of the plant, production planning information, weather forecasts or market prices for the plant's end product. Knowing how external factors affect the dynamic domain relates to the operator's knowledge of the systems surrounding the controlled dynamic domain (gap F), but is not explicitly accounted for in Figure 11, since they are loosely related to the automation problems presented in section 2.6. Enabling redirection of the control system's actions also requires that the operator can detect the current status and decide upon what action has to be taken (gap B and D), i.e. using both the observer and controller functions simultaneously.

Minimise workload from secondary tasks

Secondary interaction tasks will emerge as a side effect of using computerised control systems. Control system interaction is related to the difference between the control system user interface and the operator's conception of how it should work (gap E). By minimising tedious interaction that does not contribute to the overall system goal, work can be performed more efficiently (and the user experience will be improved).

Manage failures

To be able to assume control when automation fails is similar to avoiding the out-of-the-loop problem. It requires an adequate operator model of the dynamic domain (gap F) and the control system (gap D) together with a control system user interface developed to keep the operator prepared for rapid shifts of locus of authority (gap B, C and E). The control system's ability to determine the locus of automation failures depends on how the control system manages to diagnose itself (i.e. internal exploratory actions) and how the user interface communicates the diagnosis to the operator (gap B). How well the control system monitors the operator is dependent on what kind of operator behaviour the control system expects (e.g. input), compared to how the operator actually behaves (gap E). To ensure that the control system's functions degrade safely would require communication as to how the control system is working in order to achieve the goals of the dynamic domain in relation to the control system's own operational constraints (gap A). For the degradation to be visible it has to be represented by the control system interface (gap B and C).

2.8 Relating prescribed solutions to the dynamic domain-control system-operator triad

From having looked at and compared three classes of prescribed solutions (joint cognitive systems, situation awareness and Nuclear Regulatory Commission guidelines) to automation related problems, it was found (as expected) that prescribed measures are likely to have an impact on model incongruence. By using the gap model in Figure 11 as a basis for reasoning, it became clear that trying to reduce one gap can expand another. In the next section, efforts to reduce model incongruence are discussed and recommendations from theory are further scrutinised in relation to the proposed model.

2.8.1 How to reduce model incongruence?

Given that the dynamic domain is a complex system, a category which most process industries fall within, the idea of trying reduce incongruence by matching the dynamic domain is probably to suggest an impossible mission. Since the work system is dynamic, efforts to create a fully congruent model may fall short, since as soon as the (imagined) full model has been established the system will have changed. A chase resembling that of the tortoise and the hare (Aesop, 500 B.C.) should be avoided. So of what use is the model if congruent models are unachievable? Since the process industry work system is ever changing and adapting to its dynamic context of e.g. spot price markets, weather, and raw material quality, a key property of the work system is to adapt to change. In this respect, minimising the gaps in the dynamic domain-control system-operator triad will be a facilitator for adaptation. Variation can only be met by variation (Ashby, 1956), hence the incongruent variation as a cause of the automation related problems in section 2.6, can only be met by improving the triad's ability to co-variate. That means improving the work system's adaptive capacity.

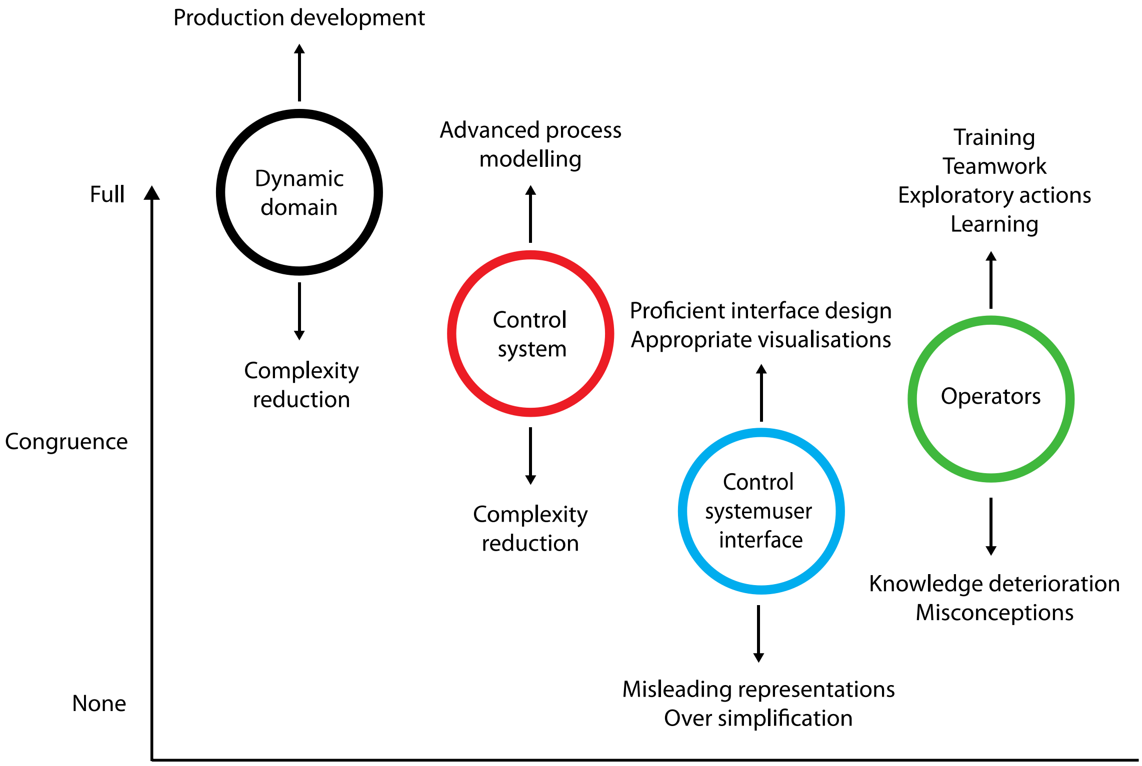


Figure 20. Factors affecting model incongruence

In practice, different approaches can be chosen to address automation related problems by improving congruence with the controlled dynamic domain. The controlled dynamic domain can be approached by working with process design, e.g. reducing complexity. The control system can also be adapted by balancing process modelling and complexity reduction. Another approach is control system interface design. Appropriate visualisations depend heavily on establishing appropriate information requirements. To reduce the gaps associated to the control system user interface information requirements and the resulting design has to reflect the functioning of both the dynamic domain and the control system. It is also important that the user interface is not subject to over-simplification since it could lead to further emergence of automation related problems due to the increase of the gap between dynamic domain/control system and user interface. Another approach to reduce model incongruence is to improve the operator's models of the dynamic domain and the control system. In the nuclear and process industries (and many other domains) simulators are used in training to improve and maintain operator knowledge. Another method is to make use of the collective knowledge of the control room team by improving teamwork. Facilitating operators' exploratory actions (see section 2.3) will also improve the learning process. Loss of skills and knowledge has the opposite effect, as the memory deteriorates over time.

The conclusion that all four circles should be addressed strengthens the case that human factors engineering has to be an integrated part of the engineering process (Cullen, 2007; Militello et al., 2010; Pew and Mavor, 2007). The engineering of the dynamic domain and the control system is by necessity limited to and dictated by what the production system should achieve. The human operator is still difficult to re-design (at least as long as neural implants and other cognitive enhancements are unavailable), which means that operator model improvement relies on the human learning process.

2.9 Modelling automated human-machine systems - conclusions

Hitherto in the research, literature automation related problems have been described as individual but interrelated (Lee, 2006) phenomena that emerge where people interact remotely with a dynamic domain mediated by a (more or less) automated control system. In this first part of the thesis, a model has been proposed that joins the emerging phenomena and describes them in a unified way. Using medical treatment as a metaphor; the intention and the expectation is that the explanatory model can aid in making the actual disease visible (how automation related problems emerge), and not only the symptoms (adverse events in operation and design flaws discovered in hindsight). In that sense, a theoretical contribution has been made, since the model has provided a new intelligible explanation (Skyttner, 2005) of automation related problems.

Now we have a unified view of this particular set of problems, the next question is: How can the model help address these problems? From looking at the model in Figure 20, evidently a multidisciplinary approach is necessary to address all gaps. Each gap and each part (dynamic domain, control system, control system user interface and operator) has their own corresponding research field(s) in process engineering, control engineering, interaction design and operator training, etc. The extensive knowledge base needed to address all gaps requires persons from different fields of expertise. Even if a single person can host all the knowledge needed, a live project in industry will have to be performed in collaboration across disciplines to reach relevant, useful and timely solutions.

Because the process industry is to a large extent a domain driven by economic (more profit) and technological (better quality) motives (Hollender, 2010), the driving force for change and improvement will primarily come from development of the dynamic domain and the control system. While the driving forces by nature are mainly technological (as compared to intentional domains, e.g. consumer products, where human needs are the natural drivers), an effect can be that development of user interfaces and operator training will lag behind. Thus, there will continuously be an opportunity to reduce the gap between the human (user interface and operator) and the technological and automated (dynamic domain and control system) parts of a work system.

One focus in this thesis is to address the gaps related to the control system user interface, i.e. gap B, C and E in Figure 11. To achieve a better control system user interface, it is essential that the designer has sufficient and appropriate knowledge together with the skill to perform the design task. In that sense, the knowledge needed by the designer will determine what is required from a method to acquire such knowledge. Supposedly, a structured systematic method will help to facilitate keeping track of the complexity the analyst will face (again, the law of requisite variety comes into play) in establishing the design requirements to be provided to the designer. (Here, 'analyst' and 'designer' refer to the roles rather than physical persons, as a single person can have both roles.)

From the previous problem descriptions and the discussions above, it follows that a method based on the model presented in Figure 10, has to:

- facilitate cooperation in terms of supporting multidisciplinary work
- help identify representational gaps
- lead to ideas on how to reduce the gaps
- aid dealing with complexity

2.10 Summary of chapter 2

In chapter 1, a model to represent supervisory work in process control has been suggested. It has been shown that the model, in combination with the concept of model incongruence, is capable of describing many of the automation related problems in a unified way. A selection of design guides to support human-control system interaction were reviewed and related to the proposed model. It was found that the prescribed solutions to automation related problems are similar to those for reducing the gaps presented in the model (Figure 11). Further, it was suggested that the ability of the agents in the dynamic domain-control system-operator triad to reduce the gaps is similar to the capacity of adapting to changing conditions in the work system. Finally, four needs for method development were posed to aid the methodification of the established model.

3 What system designers need to know in order to deal with automation related challenges

In chapter 4, method requirements were elicited to define what is demanded of a method or methodology when addressing automation related challenges. The next question is how can requirements be realised into something useful with which to address the challenges in practice? In this chapter, these requirements will be further elaborated and specified. It will be shown what questions a high utility method/methodology will need to address to face automation related challenges. These questions are presented in a framework matrix that stress how different methods can be used to elucidate different aspects of human-control system interactions. Further, a selection of existing methodologies will be evaluated and their strengths and limitations will be highlighted by mapping them onto the question matrix.

Table 7 and Table 8 state thirty-four generic and specific requirements of method capabilities derived from literature. The requirements were sorted according to model parts. The content of the requirement tables could be seen as the answer to what a high utility methodology should accomplish. The requirements specification is the target image of what a method useful for automation related challenges should be capable of. As a design aid, the role of a method is to provide the designer with a tool to systematically understand the dynamic domain, the technology and the work that people perform. The requirements established in Table 9 are used mainly to check that a method/methodology will fulfil what is needed to be useful in the domains that the thesis deals with. But how can a designer be guided to obtain a holistic view of a work system? In many ways this is the same problem that operators face when building their conceptual model of a work system, as described in chapter 1. From the design perspective, the designer has to build an appropriate conceptual model of the work system to create meaningful system representations that can be used for control.

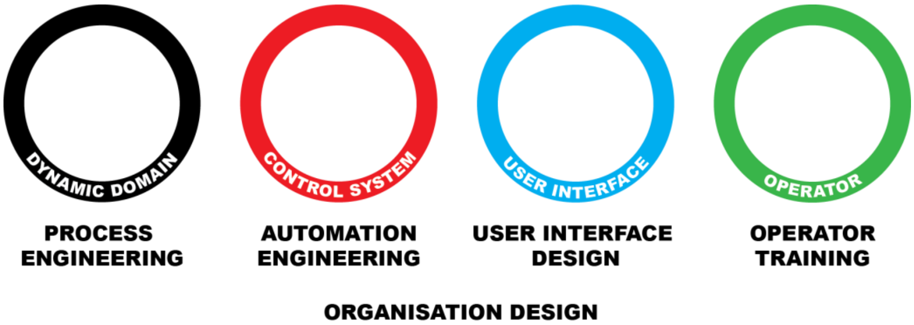


Figure 21. Example of designer roles associated with each system part

A generic plant in process industry is a complex system with a large number of tightly coupled entities that have different functions and enable the system to fulfil its intended purpose. Therefore, several designer roles are needed (Figure 21). Competencies, such as process engineering, automation engineering, interface design and operator training, are needed to enable and sustain production. The organizational designers, i.e., management, need to adapt the whole work system to the continuously changing business context.

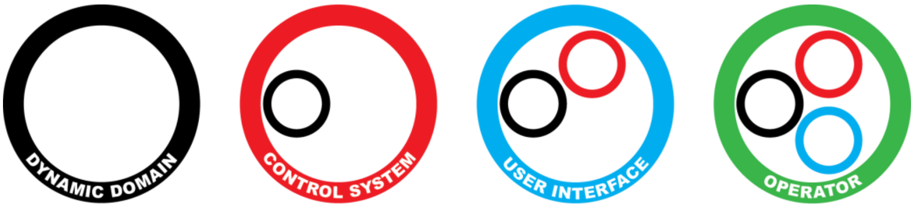


Figure 22. When moving from left to right, each part needs knowledge of the preceding parts

Following the line of reasoning established in chapter 1, the job of work system designers is to deal model incongruence across the dynamic domain-control system-operator triad. Reducing incongruence means creating designs that have the capability of managing complexity, as was discussed in section 2.3.1in terms of Ashby's law of requisite variety. In practice, complexity can be managed by incorporating adequate conceptual models (i.e., simplifications) throughout the work system. Conceptual models are not exclusively found in the heads of operators, but are also found, for example, in the control systems, to approximate the functioning of the complex and dynamic domain. Hence, the modelling effort is of interest to all designers (dynamic domain-, control system-, interface-, operator training and management) working for safe and efficient operations. One of the challenges is however, to assess and indicate when a model loses its validity by falling outside its boundaries.

The joint work system constitutes a nested hierarchy (Ahl and Allen, 1996) where the designers of the work system need to understand all system parts: the context, the dynamic domain, the control system, the user interface, and the operators (Figure 22). The operators need a conceptual model of the dynamic domain, the control system and the user interface. The control system user interface has to represent the control system and the dynamic domain. The control system needs a model of the dynamic domain for efficient control. Likewise, the designers of methods (e.g. researchers) need knowledge of how system designers work in order to be able to create useful tools for them.

Because of the nature of the nested hierarchy as shown in Figure 22, the knowledge needed to achieve congruent conceptual models are aggregated when moving from the inside (the dynamic domain) and out (towards the operators). The control system needs a model (i.e. knowledge) of the domain. The control system interface has to represent (i.e. contain knowledge) of both the control system and the dynamic domain. The operator needs knowledge of all parts, the dynamic domain, the control system and the user interface, together with knowledge of themselves and colleagues. (e.g. meta-cognition (Lau et al., 2009)).

Due to the nested hierarchy and the aggregation of knowledge, the system designer will need to build knowledge representation from the dynamic domain and outwards. Knowledge aggregation also means that achieving model congruence will be increasingly challenging when moving from the dynamic domain towards the operator, see Figure 22.

In practice, the control system does not need a perfect model of the dynamic domain. In many process industry applications, relatively simple PID controllers are sufficient for most tasks (Hollender, 2010). Neither is it feasible for the user interface to display all available information or that the operator should know everything. Despite the gaps across models, we have work systems that work well producing high quality products and plants explode relatively seldom. The fact that there are problems and that things also work well, indicates that work systems manage to stay within their boundaries most of the time (i.e., maintain control). When situations change and the work system falls outside its intended boundaries, the work system's ability to adapt to new operating conditions becomes critical.

The complexity of our (technical and social) work systems are likely to increase over time (Norman, 2010), and work systems will change continuously (Hollnagel, 2005). With the notion of complexity and rate of change, system designers will always need to consciously build adaptive capacity into work systems (Branlat and Woods, 2010; Flach, 2012; Nemeth, 2012). Adaptive capacity can be seen as a way of expanding knowledge of corresponding system parts. For example, a control system adapted to a new range of operating conditions has learned and expanded its knowledge. Likewise, an operator facing a new situation can adapt existing conceptual models to fit the new situation and will thus expand their knowledge base. Adaptive capacity could be improved by a deep understanding of a dynamic domain, but knowledge could also constrain ideas and make it more difficult to think outside the box.

3.1 Shifting perspective from gaps to matches

Gaps, as presented in section 2.5, represents something that is missing, something that is not there. From the design perspective it is easier to relate to something existing and develop it further. To facilitate thinking how identified gaps can be reduced through design activities, gaps are now rephrased as matches. By taking this turn, I also shift from (pessimistic) focus on the problems of automation to focusing on the (optimistic) possibilities of how better congruence between dynamic domain, control system, user interface and operators can be achieved through systems design.

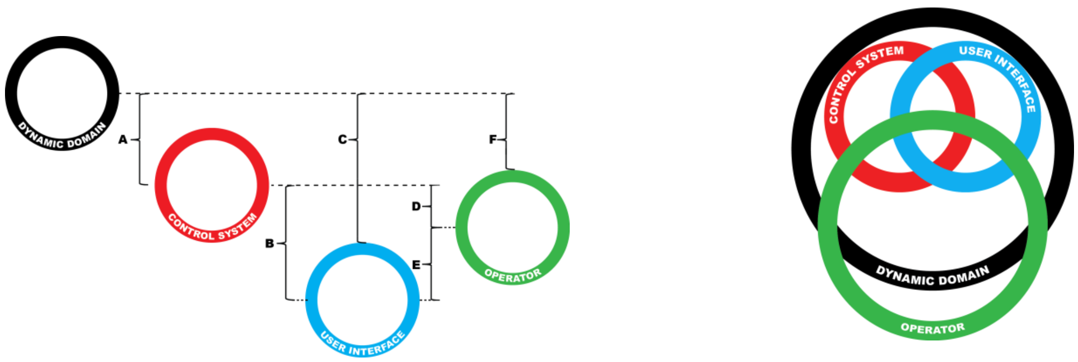


Figure 23. Moving from gaps to matches

By shifting the view from problem description to design possibilities, the gap model described in Figure 11 can be redrawn as a Venn diagram (Figure 23). Each of the gaps A to F can then be translated into model matches.

The black circle represents the dynamic domain and outside this is the context where the domain is situated. The control system (red circle) is found within the dynamic domain. The control system interface (blue circle) depicts part of what the control system is doing (the intersection of red and blue circles), but some of the control system's functions are not visible in the interface (the relative complement of blue in red). There is also an interface directly to the dynamic domain (the relative complement of red in blue), e.g., the ability to sense and act directly in the physical domain. The control system and the (digital or physical) user interface will never model the complete dynamic domain in detail (the absolute complement of red and blue in black); there will always be parts of the dynamic domain that are not covered. The operator (green circle) has a conceptual model of the dynamic domain (intersection of green and black), of the control system (intersection of green and red), and of the user interface (intersection of green and blue). The operator also has a model of the context (the relative complement of black in green) and how the context can influence the dynamic domain. (Other operators could be included and would then have a conceptual model partly covering another area, depending on their knowledge.) In the Venn diagram system representation (Figure 23) there is one area that is modelled by all system parts: the intersection between dynamic domain, control system, control system user interface and operator. In this enclosed area, each system part is unambiguous to the subsystem that exerts control. Within this enclosed area the capacity to dodge variability will be good, because the system dynamics are understandable and expected (Hollnagel, 2005). By changing the view from gaps to matches, the design challenge becomes clearer: First, how can the fully specified area be expanded to match the work domain? Second, how can the matching models be sustained (adapted) as the dynamic domain changes?

3.1.1 Expanding the match

To expand the matches according to Figure 23, all three system parts (control system, user interface, and operator) have to improve their models of the dynamic domain. Accordingly, the adaptive capacity has to be developed to match changes that continuously occur in the dynamic domain.

Expansion of models can be seen as adaptation to the dynamic domain. The dynamic domain is built to achieve a specific purpose (i.e., a heat and power plant provides district heating and electricity). When the control system designers expand the capability of the control system, it is usually done to achieve better control and/or improve safety. The user interface designer extracts information from the control system and the dynamic domain to create a representation of the technical system. The representation is adapted and expanded, based on operator information need and changes in the work system. The operators are trained to have appropriate knowledge of how the dynamic domain, the control system and the user interface work, i.e., they adapt their conceptual model to the work system. By learning from experience, team work and education, they expand their knowledge continuously. All this is done continuously over time to optimize production and maintain a safe work environment.

In the case of adverse events, where the time for adaptation is much shorter, there are other demands on adaptive capacity. Hopefully, efforts in preparing the work system to be adaptable (or resilient) will be sufficient and the work system can respond in a timely manner. But when events fall outside the boundaries drawn by what the work system expects and is prepared for, there arises a sudden need to expand or change models much more rapidly. Still technology does this quite poorly, and it became the operator's task to become creative problem solvers and respond quickly. In practice, models have to be updated as events progress.

3.2 Existing methodologies in Cognitive Systems Engineering

Given that the Cognitive Systems Engineering paradigm is a useful way of thinking, few methodologies within the paradigm focus specifically on human-automation interaction. In collaboration with Jamieson, Bisantz, Degani and Lind (2012) five model-based approaches were identified and compared. Through literature studies, an additional methodology has been identified as a potential candidate for human-control system interaction design: Applied Cognitive Systems Engineering (Elm et al., 2008) (This approach was formerly known as Applied Cognitive Work Analysis (Elm et al., 2003). The question is whether the established methodologies can fulfil the methodological requirements to handle automation related challenges, i.e. can these approaches capture the gaps and the relations between system parts that were described in chapter 1.

If it is found that any single approach can fully fulfil the methodological requirements, then the advice would be to use that particular methodology for resolving automation related challenges in process control. If gaps can be identified then there is a motivation to use the useful parts from each approach and develop something new to address automation related challenges.

In this section, three existing approaches within Cognitive Systems Engineering are chosen for a brief comparison. The purpose of the review is to contrast the existing approaches to the needs for addressing automation related challenges. The chosen approaches are Multilevel Flow Modelling (Lind, 2011a, 2011b; Rasmussen and Lind, 1982), Cognitive Work Analysis (Bisantz and Burns, 2009; Vicente, 1999), and Applied Cognitive Systems Engineering (formerly known as Applied Cognitive Work Analysis) (Elm et al., 2009, 2003).

Jamieson et al. (2012) presents two additional approaches that are not included here; the Lens Model (Bisantz et al., 2000; Brunswik, 1955) and Finite State Machines (Degani and Heymann, 2002; Heymann et al., 2001). The Lens Model is not included since it is mainly intended for modelling of joint human-control system judgments, where people make judgments in parallel with an automated system, and then to consider, accept or reject the automated output as appropriate. This is an interesting aspect of human-control system interaction, but not the focus of the thesis. Formal verification techniques, such as Finite State Machines, are also interesting to human-control system interaction, especially how these can be used to systematically identify potential problems such as mode confusion and interface inconsistencies in relation to the whole state space of the technical system (Bolton et al., 2013). The Finite State Machine method was however, left out due to the limitations of applying finite states for continuous processes, such as process control. Research on hybrid finite/continuous systems are, however, ongoing (Degani and Heymann, 2002).

Different approaches will have different strengths and weaknesses if they are developed for different purposes. Seeing methods as tools, it is unnecessary to compare them as competing concepts if it can be shown that the tools are different and address different things. So, building on the problem description presented in section 2.5, how do Multilevel Flow Modelling, Cognitive Work Analysis and Applied Cognitive Systems Engineering apply to reducing the incongruences between the dynamic domain, the control system, the control system user interface and the human operator?

Multilevel Flow Modelling

Multilevel Flow Modelling has its main focus on modelling the dynamic domain and the associated control functions in the control system. Multilevel Flow Modelling has also been used to specify the control system user interface (Lind, 1999). According to Lind (Jamieson et al., 2012), Multilevel Flow Modelling makes it possible to specify qualitative knowledge of the dynamic domain and its control, which is important for plant operation but which is implicit in current approaches to display design (Lind, 2009). Lind (Jamieson et al., 2012) also states there is a need for development of problem solving models based on end-means and whole-part reasoning, which can be used together with Multilevel Flow Modelling as templates for human machine interaction patterns in supervisory control.

At first glance, Multilevel Flow Modelling seems to be the most relevant method for dealing with automation challenges, since it explicitly models different types of semantic relations between system parts. The modelling technique does not specifically relate to automation related challenges or the corresponding gaps between models, but rather to operator support in general.

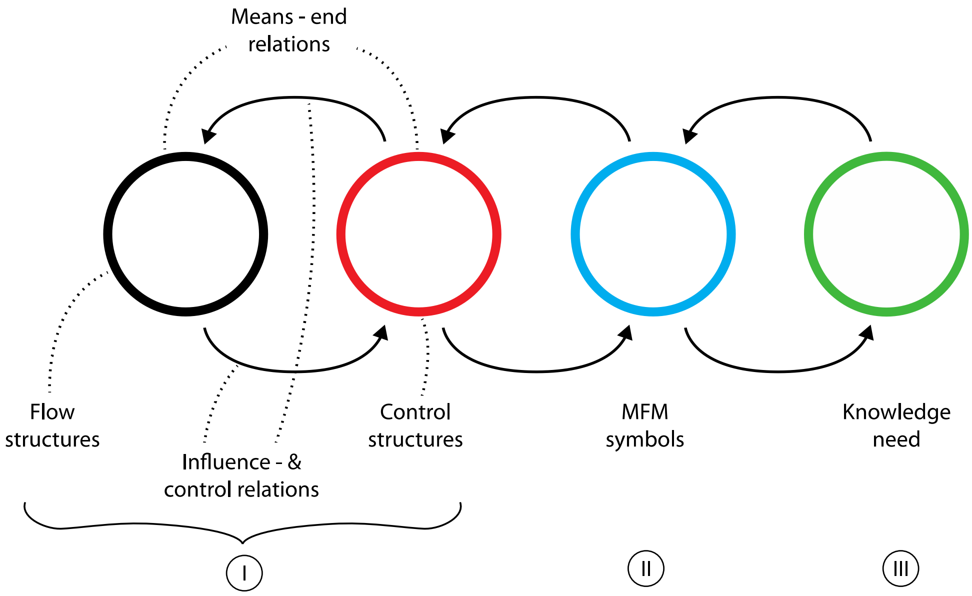


Figure 24. Multilevel Flow Modelling mapped onto the model of process control

Multilevel Flow Modelling can be mapped onto the model of process control established in chapter 1 (Figure 24). In Multilevel Flow Modelling the flow structures model the dynamic domain, while the control structures model the control system. The internal relations within the dynamic domain and the control system are described by means-end relations. Multilevel Flow Modelling also uses a defined set of influence- and control relations to describe how the dynamic domain and the control system affect each other (I). The approach has also been used to specify control system user interfaces by directly implementing the symbolic language used for modelling as interface components (II) (Duncan and Praetorius, 1992; Lind, 1999). Lind (Jamieson et al., 2012) however, states that additional presentation models are necessary to develop effective human-machine interfaces. Further, the knowledge demand imposed on operators can be defined based on the models developed with the approach (Lind, 1994). Multilevel Flow Modelling does not use gaps between the system parts as a way to describe potential problems. However, the approach has been used for advanced computerised reasoning, which can indicate potential failures if a structure or relation are lost (Lind, 2011c). Mapping in Figure 24 shows the emphasis of Multilevel Flow Modelling is on modelling the dynamic domain, the control system and on the relationship between these parts. The control system user interface and the operator knowledge are also accorded some concern. An advantage of Multilevel Flow Modelling is that it distinguishes between several types of end-means relations. The relations are defined by underlying conceptual schemata, including temporal aspects and semantic roles. These foundational schemata play a significant role as templates in the modelling process (Jamieson et al., 2012).

Cognitive Work Analysis

Cognitive Work Analysis is a framework to provide information on the design of complex cognitive systems (Lintern, 2009; Naikar, 2011; Vicente, 1999). The framework defines work requirements in terms of constraints on actors in the work system (Naikar, 2011). The framework consists of analysis through five phases (Work domain-, Control task-, Strategies-, Social organisation & cooperation- and Competencies analysis) that move from ecological towards cognitive aspects of work. A key feature of Cognitive Work Analysis is to identify work constraints that shape behaviour. Each phase of Cognitive Work Analysis identifies different types of constraints (Table 6). A set of modelling tools is available for each phase.

Table 6. The phases of Cognitive Work Analysis (adopted from Naikar (2011))

Phases	**Constraints**	**Modelling tools**
Work Domain Analysis	Physical, social, or cultural environment, including purposes and physical resources	Abstraction-decomposition space, abstraction hierarchy
Control Task Analysis	Work situations, work functions, or control tasks	Decision ladder
Strategies Analysis	Strategies	Information flow map
Social Organisation and Cooperation Analysis	Allocation, distribution, or coordination of work	All of the above
Competencies Analysis	Human cognitive capabilities and limitations	Skills, rules, and knowledge taxonomy

The first phase, Work Domain Analysis, focuses on identifying objects, processes and functions and establishing structural means-ends relations between these entities. The Work Domain Analysis is relevant to analysis of the dynamic domain, and it is debated among cognitive engineering scholars whether automation should be included in the analysis or not.

In the second phase, the emphasis is on specific control tasks at a detailed level; thus this phase stretches across the system parts, but without much emphasis on the semantic relations between parts. Each decision ladder in the second phase also represents a detailed slice of the whole task array.

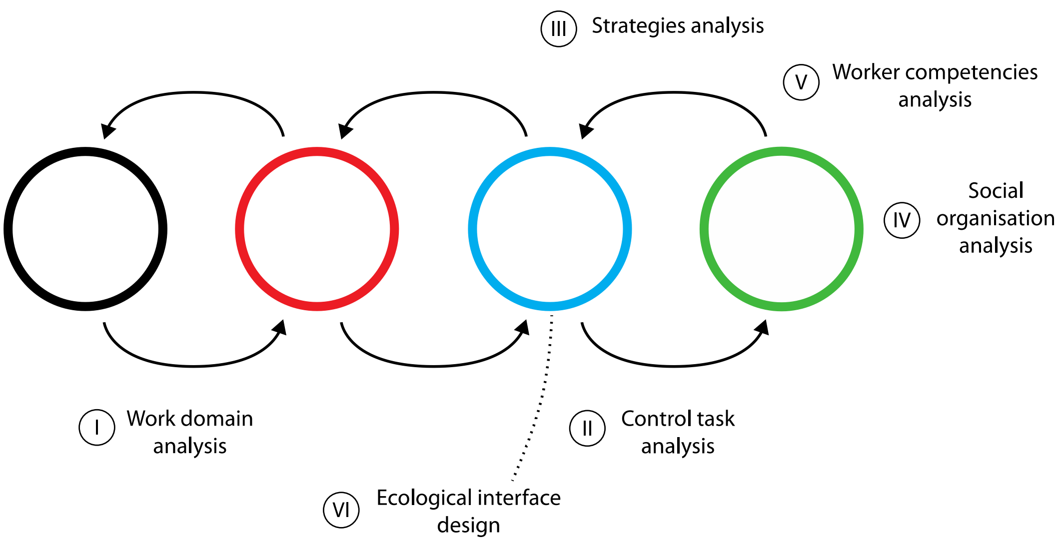


Figure 25. Cognitive Work Analysis mapped onto the model of process control

In Figure 25, Cognitive Work Analysis is mapped onto the model of process control. The Work Domain Analysis (phase I) deals with modelling the dynamic domain by using structural means-end relations. There are also a few examples of how to describe automation and the work domain in the same format (Mazaeva and Bisantz, 2007). The second phase, Control Task Analysis (II) uses the decision ladder as a modelling tool, which mainly focuses on the cognitive reasoning processes of the operator for specific tasks. The Strategies Analysis (III) deals with how different tasks can be combined to achieve a goal in the work domain. The Social Organisation Analysis shows how worker roles are distributed across work tasks and functions. The social aspects of work are important, but are outside of the scope for the model of process control in its present form. Worker Competencies Analysis based on the SRK-taxonomy is also related to the cognitive demands of the operators. Finally, the Ecological Interface Design framework (Burns and Hajdukiewicz, 2004; Vicente and Rasmussen, 1992) is based on Cognitive Work Analysis and can be used to create interface design concepts. To summarise, Cognitive Work Analysis has main focus on the dynamic domain and the cognitive aspects of work. Less focus has been put on the control system and the relations between system parts, apart from means-end/part-whole relations *within* the system parts in Figure 25. The major strength of Cognitive Work Analysis is its structured way of identifying work constraints that can be used in design to shape and guide the behaviour of actors in the work system.

Applied Cognitive Work Analysis

Applied Cognitive Work Analysis is a method for linking demands from a work domain to the design of decision support systems (Elm et al., 2004, 2009, 2003). There are five steps to the approach:

1. Creating a functional abstraction network to define the problem space based on the work domain
2. Mapping cognitive work requirements of the functional model to identify the work related challenges that need support
3. Identifying information/relationship requirements to successfully deal with the work related challenges
4. Specifying representation design requirements to define how the information/relationships should be presented to the operators
5. Developing presentation design concepts to capture the requirements needed to create effective decision support

The Functional Abstraction Network is a goal-means decomposition of the domain that has its roots in Rasmussen's abstraction hierarchy (Rasmussen et al., 1994). The goal is to achieve a system representation that will serve as the context for design of the information systems (Elm et al., 2004). In step 2, cognitive demands are derived from each part of the functional abstraction network. The demands are labelled "Cognitive Work Requirements". Cognitive work requirements can be recognition, decision making, and problem solving activities that the operators have to perform. Step 3 is to identify the information needed to deal with each of the cognitive work requirements. Information requirements are labelled "Information/Relationship Resources". The goal of step three is to identify the full set of information for decision making required in the work domain. In the fourth, step design requirements are developed to support the cognitive tasks. The design requirements specifications link the decisions within the work domain to visualisation and decision support concepts in order to support cognitive tasks (Elm et al., 2004). In the fifth stage, information design concepts are developed for the decision support system.

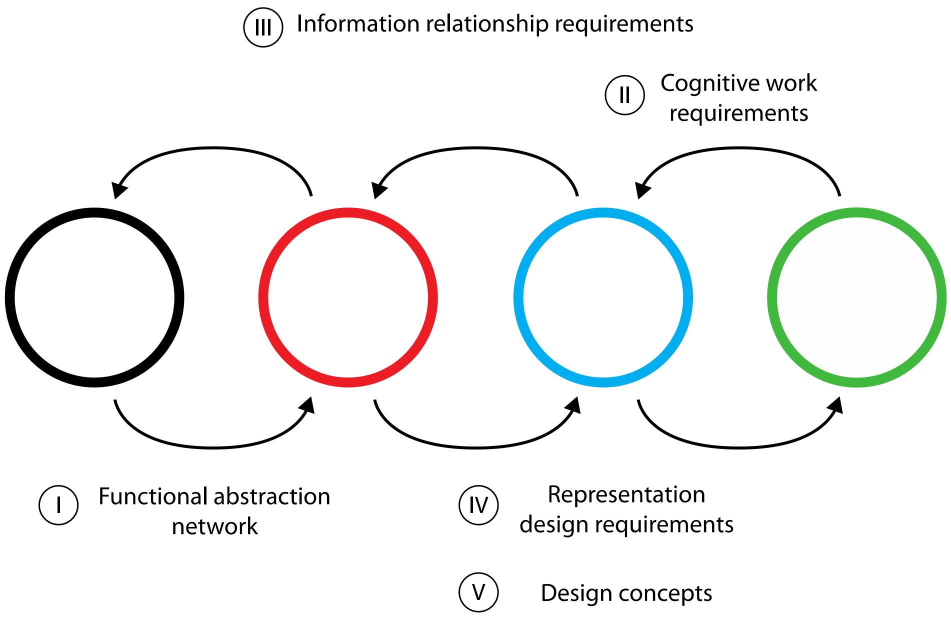


Figure 26. Applied Cognitive Work Analysis mapped onto the model of process control

The design phase of Applied Cognitive Work Analysis consists of five steps: The Functional Abstraction Network models the dynamic domain (I). The Cognitive Work Requirements (II) relates to what workers (e.g. the operators) find difficult in their work, i.e. the operators' characteristics are related to demands from the dynamic domain and control system. The Information Relationship Requirements (III) are developed to capture the functional relationships important to understanding of the work system, which means that aspects from the whole work system have to be taken into account. The next step is to specify how to represent the dynamic domain and its relationships (IV), i.e. to develop design requirements for the control system user interface. Finally, design concepts (V), i.e. the actual user interface, is developed. One benefit of this approach is the design oriented iterative method of working, which fits in well with a use oriented development process. The design oriented approach is a straightforward methodology to apply, once the Functional Abstraction Network has been established. However, the approach has no specific focus on how to model control systems in relation to the dynamic domain.

Summary

To summarise, the Multilevel Flow Modelling, Cognitive Work Analysis and Applied Cognitive Work Analysis frameworks are all very powerful and have different benefits. Multilevel Flow Modelling has its main focus on modelling the dynamic domain and its semantic relations to the control system. The first phase of Cognitive Work Analysis emphasise identification of work domain constraints through means-end/part-whole modelling. The later phases of Cognitive Work Analysis focus on the cognitive aspects of work shaped by the constraints in the work domain. Applied Cognitive Work Analysis is, to some extent, a mix of the two others, but uses a less formal network, and with a greater emphasis on the design process. None of the approaches fully cover all parts of the extended triadic semiotic model (circles and arrows in figures Figure 24, Figure 25 and Figure 26) used to describe automation related challenges. Thus, there is a risk of missing aspects of human-automation challenges when using any of these methods individually. If the benefits of the methods could be combined, a covering approach could be created.

4 Requirements elicitation for development of a viable method

In chapter 1 it was concluded that automation related problems can be approached by reducing the probability of model incongruence within a socio-technical system (Figure 11). In the remaining parts of the thesis, this approach will be further developed based on the model in Figure 10. Despite decades of previous research efforts within cognitive systems engineering, the number of technical systems built with a significant contribution from cognitive systems engineering has been small (Elm et al., 2008). The author’s experience from industrial collaboration projects is that research knowledge does not seem to come to effect for end users, at least not as rapidly as one would hope for. Several researchers have shown a gap between research and practice that has to be bridged to keep pace with the assimilation of how human factors and ergonomics can contribute to design of good work practices in general (Chung and Shorrock, 2011; Dekker and Nyce, 2004), and it is reasonable to believe that the same gap is present in cognitive systems engineering practices in particular, since this is part of the field of human factors. Therefore, the gap between research and practice has been addressed in the work of identifying method needs and requirements.

Conclusions from the model in Figure 20, invite various approaches as to how to reduce model incongruence across the socio-technical system. How should one go about such a venture of continuously working for a sufficiently appropriate match of models in the work system? The undertaking has to be continuous, since the world is dynamic and changes constantly. Hence, there is a need for us to continuously update and learn. It has to be judged what a sufficient match is, since a complete match to the dynamic domain to be controlled is neither possible (per definition of a model) nor justifiable (as it would deplete resources) or even necessary (sufficient control can be achieved with simplified models provided the operating range is clearly defined). Further, it has to be judged what is appropriate, since achieving a useful model is dependent on making relevant abstractions of the work system in relation to the goals of an activity. These trade-offs have to be successfully managed, which poses organisational challenges to the design of the work system.[3]

To be able to adapt to changing work conditions, the flow and integration of information (i.e. the connections between the parts in the model presented in Figure 10) becomes important to staying competitive in process control domains where competition is intense (Hollender, 2010). As the pace of change on the markets of production companies increase, the availability of real time production information at higher levels in the organisation becomes more important in order to be able to respond quickly to how markets change (i.e. Ashby’s law of requisite variety on a corporate level). High level automation, such as use of manufacturing execution systems (MES) and enterprise resource planning systems (ERP) integrated with lower levels of control, reflects this development.

In chapter 1, a model to describe problems and propose solutions to human-automation related challenges was presented. But what is the point of a model if it is not readily applicable in practice? In the sciences there is a tradition of using method as systematic way of inquiry. But the success of method in a development context mainly depends on the knowledge of the method user; to make the method into a tool “to get the job done” (Introna

[3] The trade-offs in macrocognitive work systems can be further reviewed in e.g. Hoffman & Woods (2011) and Woods & Branlat (2011).

and Whitley, 1997). Therefore, the continuation of chapter 4 will be devoted to investigating the requirements of a method built on the foundations established in chapter 1.

In human factors engineering literature, there are probably a couple of hundred methods available (Stanton et al., 2005). The first question to ask oneself would then be, is there really a need for another? To answer this question, we must first find out what is required from a method in order to address the challenges of human-control system interaction. Defining requirements will make it possible to compare and judge whether existing methods would suffice, and point to areas where improvement is motivated.

4.1 Defining method requirements

In this section, I will elaborate on the requirements of a method to address the challenges described in chapter 1. The requirements elicitation is based on it being meaningful to consider a method as an artefact subject to (product) development (Andersson et al., 2011; Brinkkemper, 1996; Cockburn, 2002). In order to elaborate on basic needs, and specify method requirements to guide method development, five questions were asked:

1. *What* should the method contain?
2. *How* should the method be used?
3. *When* and *Where* should the method be used?
4. *Who* are the users of the method?

Question 1 is directly connected to how the model to describe automation related challenges can be turned into a method. The purpose of the four remaining questions (Who?, Where?, When? and How?) is to map out the context of method used in human factors engineering practice. The following sections starts with a question, continues with an attempt to elucidate the question based on theoretical and empirical work, and ends with a list of specific requirements used in the following method development.

4.1.1 What should the method contain?

Defining the requirements of a method to help elucidate the model

First of all, the method should reflect the model presented in Figure 10, since this is the theoretical basis established in the thesis for addressing automation related problems. Thus the dynamic domain, control system, control system user interface and operator(s) should be represented, along with the interrelations as presented in Figure 10. The model builds upon a comparison of different representations, where a gap between representations increases the likelihood of operational difficulties. Hence, to facilitate comparison, all parts of the model need to be represented using the same language and format.

To define what a method to solve automation related problems should contain, we have to zoom in on each of the model constituents suggested in Figure 10. Before going into details, there are four generic characteristics relevant to all model parts.

First, a need to handle different levels of detail in the representation of a dynamic domain-control system-operator triad. The circles presented in the model are at one end of the aggregated-detail spectrum. By dividing, for example, the dynamic domain into smaller parts, it can be described in greater detail, moving to the other end of the spectrum. As aggregations, the circles can mean anything, and the use of the model is completely dependent on what you fill it with. To use the representation to say something about a specific socio-technical system, we have to describe each circle and each relation in more detail. By diving into the details, we can understand how a specific system is constituted; but when swimming around in the depth of details, there is a risk of losing the overall view found at the surface. A method to support design of human-control system interaction has to handle this aggregation/detail trade-off by moving fluently between levels of detail.

The next generic issue is the relations between entities across a system. While moving along, the aggregated-detailed spectrum will tell us how a system can be sectioned and to what sub-system parts belong; it will not necessarily tell us anything about why a certain entity is connected to another. Describing the means-end relation, offers a possibility to coherently describe why each and every entity is connected and the role it has in the overall system (Rasmussen, 1979). A method to support design of human-control system interaction will benefit from using means-ends descriptions, since it will provide a way to define the role of automatic control functions in relation to the controlled dynamic domain.

The third characteristic is to create an understanding of the system's dynamic behaviour. In Cognitive Systems Engineering this challenge is often phrased as creating 'system transparency' (Rasmussen et al., 1994). To describe dynamic activity, the time perspective is central, as dynamism is dependent on the flow of time. From the operators' point of view, they have to be able to see what is going on and be aided in anticipating what will happen next. Thus, a method to support design of human-control system interaction needs to capture how the control system is working to maintain control, so that the design of appropriate representations can be supported.

It is noteworthy that the three characteristics described up to this point have similarity to definitions of complexity proposed by other authors (Flach, 2012; Hollnagel, 2012; Simon, 1962). A method to deal with the problems attacked in this thesis should reasonably include the quality of 'coping with complexity' (Hollnagel, 2012). In practice this means aiding anticipation and adaptation to handle uncertainty in operations.

The most substantial generic characteristic is collaboration within a work system, where machines and humans strive towards a common goal. To reduce the probability of breakdown between automatic systems and human operators, Klein et al. (2005) propose a design for team work where human operators and the control system would become 'team players' (Christoffersen and Woods, 2002). Klein et al. (2004) presents ten research challenges for making humans and automation perform better in joint activity. Initially intended for human-robot teams, the idea of joint activity is still useful to the process control domain. In process automation terms, the first challenge is to create an agreement between the operator and the control system (a 'basic compact'). This means defining a common frame of reference, defining the common goals and how work should take place. The second challenge is to model the other actor's intents and actions in order to be able to understand and predict its behaviour. This is a challenge, both for the human operator to understand the control system, and perhaps even greater, to make the control system understand the human (an example of how the human is modelled was given in chapter 1, with a car predicting driver fatigue). The third challenge is to make operator and control system interpredictable, i.e. have an ability to predict the other teammate's actions. Fourth, the operator and the control system must be directable. In process control terms this would mean that the operator can direct and adapt the control system to aid in specific situations, and the control system can direct the operator to where problems are emerging (e.g. using an alarm system to call attention to a specific area of the dynamic domain). The fifth challenge is to make status and intentions visible to the other part, which will help explain current system behaviour. Challenge number six, is to make the visible signals understandable. If the signals cannot be interpreted the system will not support understanding and team work. This will create demands, both on how information is presented and also for prior knowledge of the operator as to understanding the technology. Challenge number seven, is the operator and the control system have to be able to take part in goal negotiations. When situations change, and the operator-control system team has to adapt, the initial agreement and goal settings will no longer be valid. The goal must then be re-negotiated and a new agreement established for continued team work. Challenge number eight says, 'planning and autonomy support technologies must enable a collaborative approach'. The planning procedure in complex and dynamic systems will invite re-planning as situations change and new demands become important. In the re-planning phase, the operator and the control system can collaborate to e.g. suggest, evaluate, and manage the resources required to reach a new goal or take a new course of action. Challenge number nine suggests that the operator and the control system should both participate in the management of attention. For the control system this will require context sensitive thresholds that can signal when a boundary condition is approaching. Information about the situational context within which the control system is functioning , e.g. when the automatic function is needed, if the conditions for use are appropriate, and conditions for terminating the automatic function, are also important to assess. Finally, challenge number ten is to control the costs of coordinating activity. Coordinating means monitoring and predicting what others do and implementing direct activities to achieve the goal as efficiently as possible. It takes time and energy to achieve and withhold coordination, otherwise it will degenerate. Therefore the cost of coordination has to be balanced, which calls for fluent interaction between operators and control systems. A method to aid analysis and design of systems where collaboration and team play function successfully, has to help deal with the challenges listed above.

Another generic aspect when looking at human-control system interaction in relation to the context of operations, is that technology and user interfaces in large socio-technical system should be consistent with each other in order to facilitate understanding (Jordan, 1998). Consistency in design (regarding dynamic domain, control system, user interface, operator training) will make it easier and quicker to learn and understand a particular system, since it can be more easily related to other systems. Consistency (and other generic design guidelines) are however, often of limited use, and design trade-offs have to be made based on the context of operations (Rasmussen et al., 1994). Automatic functions in general should be well integrated with other work practices (automatic or manual) and user interfaces in order to support operations (O'Hara and Higgins, 2010). To maintain consistency as technology and work practices evolve over time, can be a considerable challenge (Osvalder et al., 2011). Introducing (and following) corporate design standards can help in this matter.

Next, method requirements related to the specific parts of the model are defined by discussing the demands that emerged as a result of the model developed in chapter 1.

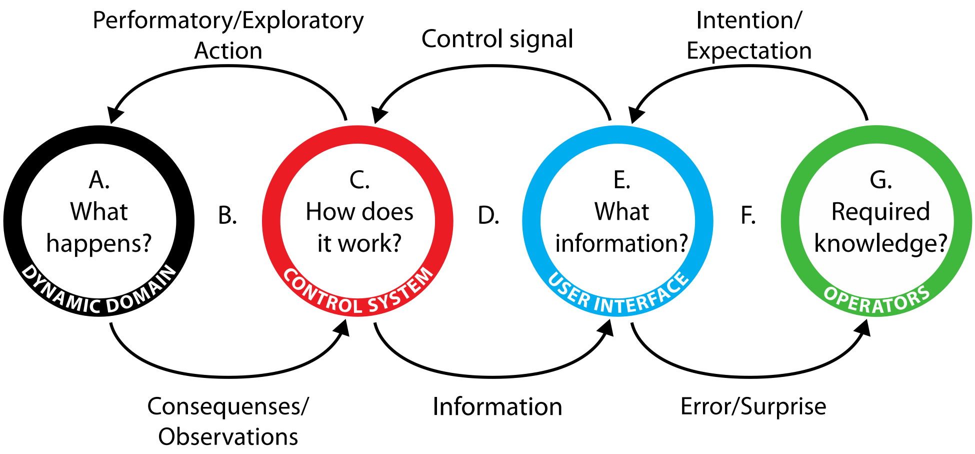


Figure 27. Method requirements

A. The Dynamic domain

The dynamic domain is the reason why the work system exists. It is through the dynamic domain that value is created, with or without automatic functions. The dynamic domain can therefore primarily be described separately from the other parts in the work system. The dynamic domain should be described so that we can understand why it is there, i.e. its purpose. Further it must be described what objects are present in the dynamic domain, i.e. a representation of the physical things used to achieve the purpose. And it would be useful to know what the physical things are capable of, i.e. a description of the functions that the physical things can achieve. By using purpose, function and objects, it would be possible to describe the static properties of a dynamic domain. But we are also interested in what happens over time, i.e. the dynamic behaviour of the system when parts come to action. Therefore, the dynamism of the dynamic domain must be captured by the method. The control system will act on the dynamic domain to regulate it. Hence the method must represent the dynamic domain thoroughly, and in sufficient detail, so that all control system activity can be related to the dynamic domain's purpose, functions, physical structure and dynamic behaviour.

B. Dynamic domain-Control system relations

To understand how the control system affects the dynamic domain and vice versa, relations between the control system and the dynamic domain must be represented explicitly. It is not enough to say there is a relation between a part in the dynamic domain and control system function. It must be described what kind of relation it is, in order to understand what the control system can do and achieve; e.g. will the control system activate, maintain, or suppress a function in the dynamic domain? Lind (Lind, 2011b) has defined several different types of this kind of dynamic domain-control system relationship.

C. Control system

As in the dynamic domain description, the control system's purpose has to be described to make it possible to understand what the control system does. The method has to capture the control system's intentions. An intention can be expressed as the goal in relation to the current status, together with the available means of achieving the goal. By having the ability to describe these aspects, the control system's intention can be represented. If a specific resource cannot be used by the control system to reach a goal, or if the control system has difficulties or fails, these aspects should also be captured. This requires a way to represent the control system's dynamic work process, in other words the control system's activities in relation to its context. Different control system functions can have different purposes, e.g. both maintain safety and performance optimisation. To achieve its purpose, the control system shall have defined goals (e.g. keep a temperature below T degrees) that have to be captured by the method. The control system's actions are set by the rules (i.e. the algorithms) defined by the control engineer. Control algorithms are the control system's basis for action, and have to be visible and comprehensible in order to facilitate understanding of the control system's behaviour and capability. By making the algorithms transparent, operators can perceive the control system's intent more easily and build a mental model of how the control system works (Lee, 2006). This way, operator-control system team work can be improved (Christoffersen and Woods, 2002). The requirement for representation of the control system to be comprehensible means the method has to deal with complexity. Since the control structures can possess a high level of complexity in terms of, for example, number of items, interconnections and nested loops, the method has to be capable of representing these relations.

D. Control system - User interface relation

The relation between control system and user interface will define how data from the control system is chosen for representation in the user interface. Information should be chosen based on how a representation of the dynamic domain is to be created and how the control system acts to control that dynamic domain. In the dynamic domain, there are constraints that will define the range of operation, i.e. specify the possible behaviour of the system (Naikar, 2011). These constraints have to be identified and represented (Burns and Hajdukiewicz, 2004). The control system acts to maintain the dynamic domain within these constraints, and the domain constraints can be used to set and explain the contextual boundary conditions for control system activities.

E. Control system user interface

To overcome the difficulties of understanding what the control system is doing and why, the information in the control system user interface is crucial. Primarily, the control system user interface has to show information about the dynamic domain and the control system, the interconnections, dependencies and inner workings. This information has to be presented in a format that does not impose unnecessary cognitive load on the operator, i.e. the information should be adapted to human perceptual capabilities. The operator should be provided with an insight to the dynamic domain (Woods, 2005). The user interface should present the means for action; how the system can be directed in relation to current goals. To begin with, data has to be presented in an integrated way (due to the vast amount of available data), in relation to what it represents in the dynamic domain, and given a context that provides meaning (Woods, 2005). Integration will help overcome keyhole effect (Woods, 1984), by making it possible to view large parts of a dynamic domain at a same time. The aggregated overview information has to be contrasted with the possibility of moving down to a detailed level by decomposing integrations into its sources (O'Hara and Higgins, 2010; Woods, 2005). By enabling the shift of viewpoints from aggregated to detailed, for example by hierarchical modes of presentation, the trade-off between data driven and goal driven processing can be supported (Endsley et al., 2003). Such interface qualities are important when representing process control, since they allow pinpointing the sources of an effect detected at a higher level, e.g. in an aggregated presentation. From the other way round, it will aid seeing what effects a malfunction in a specific component or object might have on goal fulfilment. Another important user interface aspect of a dynamic domain and control system is how to represent time. To facilitate understanding of what the control system does, and what happens in the dynamic domain, it is important not only to see what has happened (history), but also to provide features to assist projections of future status (Endsley et al., 2003; Woods, 2005). Representing information drawn from a complex system to provide the possibility of shifting and contrasting multiple perspectives will aid understanding (Woods, 2005). This is not specific to user interfaces; information can be gathered from many other sources, but the user interface can help to contrast views when different types of information are used. For example, Jamieson et al (2007) suggests that different types of interfaces will support operators in different aspects of work. As pointed out in section 2.6.4, calibration of trust is a major concern in human-control system interaction. Therefore, the control system user interface should indicate the reliability of control system functions to enable the operator to calibrate trust (Lee and See, 2004; O'Hara and Higgins, 2010).

F. User interface - Operator relation

Control systems in process control can work continuously for long periods of time without interruption and changes can be slow and difficult to notice. Therefore representations need to highlight changes and events (Dekker and Woods, 2002). It should be possible to scan and detect abnormality without difficult cognitive work, and support should be given as to what to expect and where to look next in a complex environment. By supporting anticipation, the operator can be prepared and avoid surprises. The ability to revise focus and adapt to changing conditions is closely related to anticipation. As described in section 2.6.5, automatic functions can mask system degeneration because it compensates failures. To avoid surprises, it is crucial that control system activities are transparent so failures can be revealed and understood without leading to rapid brittle breakdowns. Providing transparency is, therefore, a way of contriving to provide the operator with time to reflect and respond, rather than be forced to immediate action.

When information need is contrasted with the interface design, the result will be a trade-off between what knowledge should be represented externally (in the interface) and what knowledge has to reside internally (operator competence) (Norman, 1993) in order to achieve model congruence.

G. Operator

From a human-centred perspective the dynamic domain, control system and control system user interface can all, to some extent, be designed with the human operator in mind. A dynamic domain can never be designed just to be easy to understand, but design choices can be made to avoid excess complexity. A key issue is that the representation of a complex control system in e.g. a user interface must not be overly simplified so that although it appears easy to understand, it actually contains hidden complexities. For example, Woods et al. (2005) suggests that the pressure to narrow and over simplify a problem must be balanced by providing means to be comprehensive and broaden scope in the effort to stay in control.

Finally, the operator knowledge (conceptual models) and skills necessary to understand and operate the plant can be extracted based on how the system works. (Note that this implies shaping the operators' conceptual models to the job, at the same time as the user interface should be shaped to support human perception, decision making and action abilities.)

To access automation related problems, representations have to be sufficiently sophisticated to capture the problems in detail. More importantly, representations must be able to describe how things go right (Hollnagel, 2011). Then operational variability can be seen as deviations from the normal mode of operation.

Summary of requirements for a method capable of facing automation related challenges

In summarising method requirements there are generic requirements and requirements specific to the parts of the model. First the generic requirements are listed, followed by a table of specific requirements.

Table 7. Generic method requirements

Hierarchy	Relations	Transparency	Collaboration
The method should:			
- help the designer deal with complexity by enabling fluent shifts between levels of detail and abstraction - have a unified format to describe dynamic domain, control system, control system user interface and operator knowledge.	- help define interconnections and dependencies by explicitly representing relations between dynamic domain and control system	- help define what have to be shown to visualise how the control system is working by: - avoid black boxes and make control system's activity transparent - show how algorithms work and explain the control system's reasoning process	Enable a collaborative approach by: - facilitating predictability of other team member actions - defining a common frame of reference between the operator and the controlled system - defining the common goals between the operator and the controlled system

Based on the review above, a summary of specific method requirements are presented in Table 8. Method requirements are divided into columns to reflect the model presented in Figure 10.

Table 8. Requirements for method capabilities to support automation related challenges

Dynamic domain (D)	D <=> CS	Control system (CS)	CS <=> UI	User interface (UI)	UI <=> Op.	Operator (Op.)
The method should:						
- enable represen-tation of the purpose(s) of the dynamic domain - enable represen-tation of the physical objects in the dynamic domain - enable represen-tation of the functions of the dynamic domain - enable represen-tation of the dynamic behaviour	- define how control system activity is related to the dynamic domain purposes, functions, physical structure and dynamic behaviour - identify and distinguish between different kinds of relations	- enable representation of goal(s) in relation to current status - enable representation of available means to achieve the goal(s) - enable representation of control system dynamic behaviour - aid how to make control algorithms visible	- help defining what the available means are for achieving a specific goal - help defining what data should be represented in the UI - aid the choice of data to visualise for support of correct mental models - aid pointing out where reliability of automatic functions have to be indicated	- aid defining the UI information content (dynamic domain+control system) - aid defining the operator's means for action in the UI - aid defining how data can be integrated in the UI - aid defining how the operator can shift between multiple perspectives - aid defining where time should be explicitly visualised (history-now-projection)	- aid collaboration by pointing out where status and intentions of the operator and the control system can be made visible - aid defining how management of attention can be achieved in practice	- enable handling the trade-off between avoiding excess complexity without over simplifying - support consistency in design - help defining necessary operator knowledge / competency

4.1.2 How should the method be used?

A typical setting where the human factors engineering method will be used is the project meeting, where plant design changes and the requirements for control system design are discussed. As described earlier, the analysis process by necessity needs to incorporate persons from different disciplines who can collaborate to achieve the goal, namely to produce design requirements useful to other system designers (e.g. process- or automation engineers) at a later stage in the design process. In a sense, collaborative work can be described as a learning process, since participants could be subjected to seeing a gap in their own perceptions when these are exposed to the views of other participants. The gap in knowledge can then be closed by engaging in discussions as to how other stakeholders' views of the analysed system could affect one's own area of expertise. Ultimately, new insights can challenge perceptions of how the domain under analysis actually works, as underlying conceptual models are challenged by other experts.

As a mediating object the method should catalyse collaboration across disciplines and could possibly function as a platform, where the input from different participants elucidates different aspects of the analysed socio-technical system. In which case it is important for the method to be capable of capturing each participant's view.

Through collaboration, a method can be used as a catalyst to facilitate the collaborative learning process. However, knowledge transfer can only take place if the knowledge is articulated, externalised and communicated (Cummings and Teng, 2003). Hence, a method should help articulate and externalise knowledge and provide an output that can be communicated. The communication and externalisation of knowledge will then aid the establishment of shared understanding.

In studies of requirements, elicitation processes in information systems design concrete aids that could be provided by a method that has been identified (Chakraborty et al., 2010). First, a method can help establish a working relationship between participants, since a structured method offers a starting point and a procedure as to where to begin cooperation. A method can also help create a clearer understanding of a problem domain, which enhances the clarity of the broad needs of a system. A method can help articulating the problem definition by creating an external representation of the problem definition boundaries that can show the consequences of how the boundaries are drawn. A method can also help see how overall business objectives affect the work system as a whole. Further, a structured approach can help identify gaps in the established design requirements and pinpoint where further, more detailed investigations might be needed.

In a study made by the author (Andersson and Osvalder, 2013), it was found that method practitioners have to adapt or 'tweak' formal methods to fit them to current project needs. Tweaking often means loosening up formality and allowing more variability in how a method is used, thus meeting the variations of the working conditions in a more effective way. Practitioners also stress how systematic work and systematic documentation ensures that method results are tractable. Traceability of design requirements are important, since decisions can be traced back to where the needs emerged. Further, practitioners indicate that academic HFE methods in general are seen as tedious and boring to perform. This is a serious problem, especially as HFE as a discipline is struggling to become an integrated part of the organisation and the system development process. The method should aim at being stimulating and meaningful for the individual participant, since this will improve intrinsic motivation and creativity (Amabile, 1998, 1997). The level of ambition required by analysts was mentioned as an issue by the practitioners. If a method can be designed to be used irrespective of the analyst's level of ambition, it will always be possible to use the method, regardless of project constraints. However, it could be the case that practitioners will always choose the easiest variant of the method. There is a risk of this damaging HFE reputation, if results produced from such 'discount' methods (Cockton and Woolrych, 2002) are not thorough enough to provide a basis for high quality design decisions. Another expressed need was explicit descriptions of methods to help jump-start an analysis effort. Explicitness is vital

to achieving common ground in understanding how and why a method should be performed across participants in a multidisciplinary team.
Practitioners brought forward measurability as one of the key issues in motivating HFE effort in industry. According to interviewees, if measurability can be improved, the chances of impact on an organisational level are considerably increased.

4.1.3 When and where should the method be used?

Work where it is possible for the model to come into practical application is found mainly in the industrial domain. It is in the process and energy industries that the greatest impact can be achieved. The choice to focus on industrial use is made based on the author's experience of collaborating with industry and industry's concern with academic methods and tools as being tedious to perform and of not producing enough useful material to justify the effort of their usage (Andersson and Osvalder, 2013; Andersson et al., 2011). The stance taken in the thesis is that, if a method can be adapted to its intended user and the demands from the context where it is used, there is a better chance that (i) the method will be frequently applied and (ii) that the results provided by the method will be appropriate and better integrated with system development context. This idea is supported by approaches in the fields of method engineering (Brinkkemper, 1996; Henderson-Sellers and Ralyté, 2010) and agile method development (Cockburn, 2002).

The design process

The process of developing a new technical system, be it a toaster or an industrial control system, means a transition from an abstract idea to a concrete artefact. The development process can be roughly divided into three parts: needs, industrial design and engineering design (Bligård, 2012; Ulrich and Eppinger, 2004). The starting point is determined by the novelty of the product and the heritage from creating similar designs in the company. Primarily, a need for a new design is somehow identified, motivating the start of a system development effort. The need can emerge e.g. from potential customers or from the need to replace old equipment. The identification of a need leads to an idea and conditions for further development (Bligård, 2011). In the industrial design stage it is decided how the artefact should function, what it should look like and how the user should interact with it. Gradually, basic requirements are turned into specifications used to guide and later evaluate the design. In the engineering design stage, the product is built and assembled according to the specifications created in the previous stage. Prototypes are made to test different types of technical solutions. Result from the engineering design stage include, for example, technical drawings, production specifications and assembly instructions (Bligård, 2011). Figure 28 describes an example of how the development process moves back and forth between design and requirement specification activities.

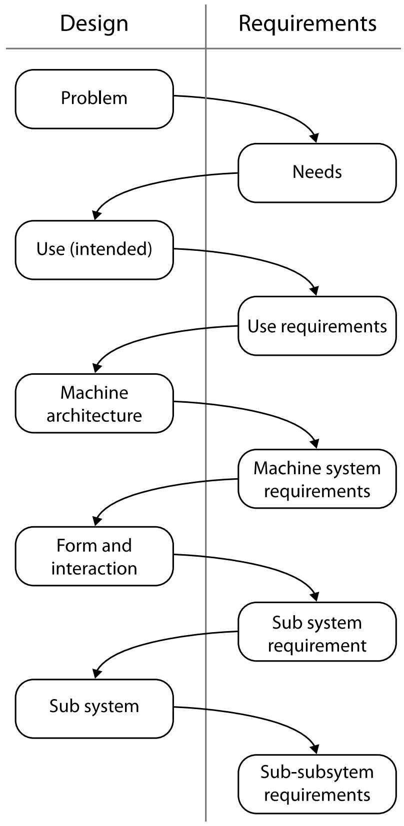


Figure 28. The figure shows a generic product development process. Activities move back and forth between design and requirements specification (Bligård, 2011)

The development process is iterative in its character, since modifications and adaptations have to be made continuously throughout the working process. The iterative process is important, since the new design of e.g. a plant process alteration, with control system and user interface modifications, can change the strategies of how work is done. Therefore, the analysis cannot be based on how work is performed before the change, because it will no longer be valid once the alteration is done. In this sense, human factors engineering work is to aim and try to hit a moving target. Work is analysed and new designs are suggested, which in turn will change the work direction once more (i.e. the "envisioned world problem" (Woods and Christoffersen, 2002). Here, rapid iterations will aid design work as this closes in on the final solution. As design work continues it gradually becomes more expensive to make changes to decisions already made, since each decision builds on earlier agreements. Therefore it is important for results from needs and requirements elicitations to capture as many aspects as possible from different stakeholders' viewpoints early on in the design process. Different perspectives from different areas of expertise, or groups within an enterprise, will help avoiding misses that have to be corrected later on in the development process (Bligård, 2011). It is important that stakeholders can influence development during the design stages, which can be facilitated by an iterative development process. In this sense, the establishment of appropriate design requirements has much to gain from incorporating different perspectives into each development phase. To reach agreement when establishing well defined and useful design requirements, is therefore a highly collaborative exercise.

One main aspect of getting methods into practical use, is to make them fit into the overall work process in the company (Andersson and Osvalder, 2013). For integration purposes, analyses performed must yield the requirements needed to inform the human factors design, and provide outputs in a format asked for by other stakeholders. The method is a potential platform for collaborative requirements elicitation. The collaborative process during requirements elicitation is further examined in the following section.

Collaboration processes during elicitation of design requirements

In their research of the requirements elicitation process in information systems development, Chakraborty et al. (2010) presents a study with an extensive literature review and empirical material using a grounded theory approach. No equally thorough research on requirements elicitation was found within the human factors literature, which motivates the search in other fields of research (information system design) to identify relevant and useful findings. Based on their studies, Chakraborty et al. (2010) suggests a model where collaboration work can move between four collaborative states: scoping, sense-making, dissension and termination (Figure 29). Each transfer (arrow) between states is affected by enablers and inhibitors that can make the work more efficient or obstruct the team from establishing useful requirements that can be used in design. The goal of the process is to reach the termination state with a common understanding between analysts and user representatives and a useful and appropriate set of design requirements.

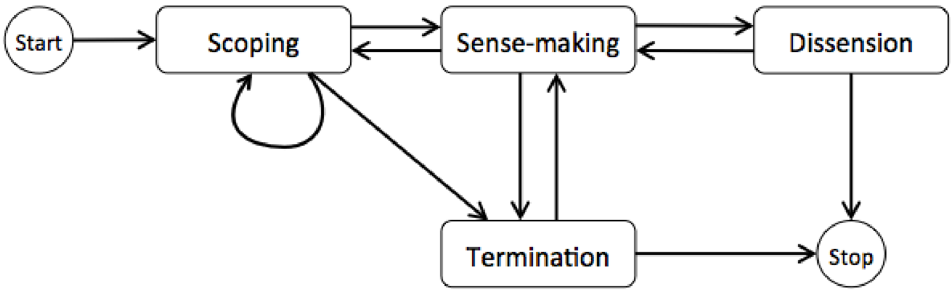


Figure 29. The collaborative process in requirements elicitation. Adopted from (Chakraborty et al., 2010)

In the **scoping state** it is mainly the user representatives who explain to the analysts how they perceive the goal(s) of the work system, and the needs they have. According to Chakraborty et al (2010), the scoping state of requirements elicitation means a: '...formal breaking of the ice [...] where the user representatives engage in initial articulation of the problem domain [...] and attempt to get to know each other to establish a working relationship.' In this state, the analysts and user representatives can still have divergent images of the goals to be met. In the **sense-making state,** the participants try to understand the other party's perspective of the problem domain. Through dialogue, the project goals are scrutinised to develop a thorough understanding of the work system. The goal of the analyst is to collect as much information as possible by 'tapping in detail into the domain knowledge of the user representatives'. If successful, the scoping state will lead to a better and common image of the problem domain. In the **dissension state** the focus is on resolving difficulties and controversies that emerge in the sense-making state. Due to potential disagreements, conceptual models of the analysts and the user representatives are often different as regards details of the project or a specific requirement. Chakraborty et al (2010) states this is resolved through dialoguing and effort to understand the others' point of view. In the **termination state** gathered agreements are presented in a requirements specification and a plan for action is agreed upon. A shared frame of reference should now have been reached, and involved stakeholders can start to cooperate in a development process directed towards reaching the common goal of the project.

In addition to the aspects described above, the importance of trust between analysts and user representatives was stressed in the study. Trust is described as ”the glue that holds together any collaborative and knowledge transfer effort” (Chakraborty et al., 2010). Further, Chakraborty et al (2010) identified a number of enablers and inhibitors that affect the progression in each state and triggers that lead to transition between the states. Complexity and tacitness are identified as important inhibitors, together with lack of congruence in understanding.

The broad conclusions from the work of Chakraborty et al. (2010) regarding how to facilitate a collaborative requirements elicitation process are to:

(i) Promote knowledge transfer, trust and establishment of shared mental models between the participants.
(ii) Facilitate progress in each of the scoping, sense-making, dissension and termination states. Progression is reassured by participants having the required knowledge and achieves a congruent understanding by means of communication.
(iii) The transition between states is facilitated by several different triggers[4].

Summary of method demands derived from the requirements elicitation process:
Considering the conclusions from Chakraborty et al. (2010), the following requirements are of use for method development to support human-control system interaction:

A method should:

- work as a means to externalise knowledge
- support communication between participants
- has to be able to represent the work system and capture the problem scope

4.1.4 Who are the users of the method?

In this section, the intended users of the method are identified and described. The knowledge and competencies needed for successful method use are also determined.

First of all, the method suggested in the thesis is primarily intended for industrial practitioners rather than scientists (this however does not exclude scientists as potential users). The reason for focus on industrial practitioners is that the author has perceived the greatest need to be for a method that will function in the industrial context (Andersson and Osvalder, 2013; Andersson et al., 2011). In the academic context, the prerequisites for use of methods are quite different compared to industry. The most significant difference is probably the basic aims of the two domains; while industry primarily looks for solutions that work, academia is mainly interested in the scientific truth (Chung and Shorrock, 2011; Rouse, 1985; Vicente et al., 1993). This is a broad generalisation, not necessarily valid for all organisations. However, there is a generic trade-off between being efficient and being thorough, and often the corporate world are more prone to embrace efficiency, while academic institutions tend to honour thoroughness in research work. A trade-off is never black or white; it is always a gray area and a balancing act of comparing different aspects with one another. Academic research

[4] The many triggers are not specified further here, but helped to formulate the tangible aids presented below. The interested reader can find a full list of triggers in Chakraborty et al. (2010)

can be very pragmatic and applied, while corporate research efforts can be extremely focused and deep. Nevertheless, the research-practitioner gap has been acknowledged as a problem in human factors discipline, since the aim of research activities is most often to inform design (Chung and Shorrock, 2011). In this thesis, the creation of a use-centred method is an attempt to bridge the research-practitioner gap by designing a useful tool that can function in the industrial human factors engineering context.

In chapter 1 it was concluded that automation related problems can be addressed by studying the representations and the gaps between representations, as presented in section 2.5. Based on the four circles of the model (dynamic domain, control system, control system user interface and operator), we can assume that knowledge of these parts and the relation between the parts, will be of use when modelling work in the dynamic domain-control system-operator triad. Who are the people that possess relevant and necessary knowledge? Primarily, the in-depth knowledge of process equipment functionality is located with the vendors of the technical systems. Knowledge of the dynamic domain (the process equipment in action) is possessed mainly by engineers and operators who work in and with the dynamic domain on a daily basis. Control engineers at the plant, together with the designers of the plant control system, possess knowledge of the control systems in the plant. There are often several control systems working in parallel in different parts of a plant, which further stresses the need for expert knowledge of several technical systems. Regarding the control system user interface, this is usually a default design made by the plant designers/control system vendors that will be maintained and altered by persons at the plant responsible for control system interface screen images. At the plants visited by the author, these have been consultants or experienced operators with special education in how to modify control system interfaces. Interaction designers, with appropriate technical understanding, could also be reasonably expected to possess the required skills. There are always limitations as to what can be done graphically with the control system interface, and this is a challenge facing control system interface design. Limitations are set mainly by hardware and by the control system vendor's graphical libraries (Osvalder et al., 2011). Finally, knowledge of the human function as a supervisory controller is mainly found within people possessing skills in human cognition, i.e. psychologists, behaviour scientists and human factor specialists. The physical working environment is another important area where ergonomists and human factor specialists have the skills to improve physical ergonomics and, for example, avoid fatigue and work related injuries. One key aspect the roles mentioned above have to take into account and safeguard, is the hands-on, experience based knowledge possessed only by operators who have worked as supervisory controllers and field operators (NUTEK, 1996). This type of knowledge is often tacit and difficult to verbalise, and attainable only through practice. Therefore, the possibility to learn from exploratory actions (Bennett and Flach, 2011), should be maintained.

The broad range of competencies (e.g. different types of technical engineers, operators psychologists, human factors engineers, ergonomists, etc.) needed to inform different parts of system representation, all possessing important knowledge and abilities to improve different aspects of the work system, demonstrate that the effort to limit the gaps between system parts has to be a joint multidisciplinary effort. This conclusion is in line with product development research in general (Almefelt, 2005; Araujo, 2001; Boff, 1987) and requirements elicitation in particular (Bligård, 2011; Engelbrektsson, 2004).

Knowledge needs to create an appropriate system representation

Two needs can be derived from the above discussion. First, there is a need to retrieve knowledge regarding the model constituents in order to understand and bridge gaps. Second, there is evidently a need to involve different types of expertise due to the broadness of model scope. This knowledge can be found among people with different backgrounds and skills. Given these demands, the method must support multidisciplinary collaborative work between for example, engineers, human factors experts and operators, to facilitate the requirements elicitation process. These people should all be part of the design process, and can, to some extent, all be called ‘designers’ because they design, suggest and influence final technical solutions from their particular point of view.

What supports multidisciplinary collaborative work? According to some researchers, one of the greatest hindrances to multidisciplinary work is the difficulty of appreciating and understanding the view of other disciplines (Boff, 1987; Waterson and Kolose, 2010). Problems are viewed primarily from own perspectives and with the constraints of own contexts. Collaborators in the design process do not necessarily share the same view or constraints, even within the same organisation. Different departments can have separate budgets and will be affected in different ways by a design decision. As described by Chakraborty et al. (2010), understanding and knowledge of the problem domain is a key aspect in the requirements elicitation process. Different disciplines use different technical languages and jargon which can lead to ‘tower of babel’ symptoms (Boff, 1987), which result in misunderstandings between disciplines.

Based on the fact that work when using the envisioned method will be a collaborative multidisciplinary effort, the following method requirements can be stated:

- The method should facilitate taking another discipline’s point of view into account
- The method should provide a way for a multidisciplinary team to communicate using a common language
- The method should produce the requirements needed to inform the HF design, and provide output in a format required by other stakeholders in later design stages.
- The method should use terminology that can be understood by all stakeholders in order to facilitate communication and avoid misunderstandings.

4.2 Summary of established method requirements

To summarise the elicitation of method requirements, requirements have been collected in Table 9. When the summary was made, it was found that requirements can be grouped into three broad categories: (i) solve the problem, (ii) support design activities, and (iii) be viable in an industrial systems development context.

Table 9. Summary of method requirements

Method criteria	Method requirements to meet criteria
A. Capability to address automation related challenges	Two sets of requirements have been established. The first set of requirements is valid for the whole system. The generic requirements are presented in Table 7. The second set is divided according to the specific parts of the model presented in Figure 10. These requirements are presented in Table 8.
B. Support design	• The method output should be design requirements useful for system design. • A method should work as a means to externalise knowledge. • A method should support communication between participants. • Make the representation directly readable by others, irrespective of background knowledge, to facilitate communication and knowledge transfer. • The method should facilitate taking another discipline's point of view into account. • The method should provide a way for a multidisciplinary team to communicate using a common language. • The method should support traceability of design requirements, so that solutions can be traced back to design decisions where the needs emerged.
C. Industrial viability	• The method should allow variability in how a method is used in order to allow adaptation to different industrial contexts. • The method should use terminology that can be understood by all stakeholders to facilitate communication and avoid misunderstandings. • The method should explicitly state what should be done and why. This requirement stresses the need for a pedagogical approach to method design. • The method should support the trade-off between efficiency and thoroughness by allowing for different levels of ambition in an analysis. • The method should produce the requirements needed to inform the HF design, but also give outputs in a format requested by other stakeholders in later design stages. • The method should support identification of measurable indicators that can be used to assess and follow up system performance. • The method should aim at being stimulating and meaningful for the individual participant, since this will improve intrinsic motivation and creativity.

These three types of criteria are important from different perspectives. The most important group of requirements is group A, concerned with solving automation related problems. Without a valid method to address the right things, method development effort would be meaningless, at least from the perspective of wanting to resolve the issues that occur in human-control system interaction. The second group of requirements (B), concerns how to support system design and is vital from the engineering perspective. If the analysis performed with the method fails to provide information about how to design a better system (i.e. achieve the solutions needed to solve the problems), the analysis effort will be questionable. Finally, group C is particularly relevant to industrial use. If the working procedure used to perform the method is too cumbersome, or if the initial learning curve as to how to use the method is too steep, no one will use the method, no matter how good the results (Andersson and Osvalder, 2013). Naturally, this is dependent on the working context and level of knowledge of the method users. For example, in an organisation with a high level of human factors competence, more advanced human factors methods can be used more easily. Available resources are also a critical factor. This way the ecology of the work organisation presents both barriers to, and facilitators of, human factors engineering work in practice.

The key point here, is that in an industrial business setting it is not until all three groups of requirements have been fulfilled that a method becomes truly useful. An analogy can be made with Nielsen's definition of usefulness (Nielsen and Hackos, 1993), saying that Usefulness = Utility + Usability. While group A and B concerns the *utility* of the method, the third demand concerns the *usability*. By meeting the demands of both utility and usability, a useful method can be attained powerful enough to solve problems and be attractive to human factors engineering practitioners in industry.

5 The System Representation Matrix – description and use

The purpose of the System Representation Matrix is to enable analysis of human-machine-environment systems in order to detect representational gaps. The aim of the method is to generate information useful for increasing the representational match between the operator knowledge, the user interface, the control system and the dynamic domain. The result of method development effort in this research work forms the basis and procedure for building a system representation. In practice, the intention is for the procedure, together with the system representation, to become a mediating object that enables members of a multidisciplinary development team to reason around how representational design can support operations.

5.1 Integrating the means-ends hierarchy with the triadic model of human-machine systems

To be able to expand on model matches, we first need something to match with, i.e., a representation of the dynamic domain. One way of modelling the domain that has been proven useful within cognitive systems engineering, is by the application of means-ends abstraction hierarchies (Rasmussen et al., 1994).

The means-ends abstraction hierarchy allows description of the dynamic domain, the control system, the user interface and operator knowledge by using the same taxonomy. Hence, it is a powerful way of achieving comparisons across system parts. The abstraction hierarchy has been applied to work domain analysis as part of Cognitive Work Analysis methodology (Lintern, 2009; Naikar, 2011; Naikar et al., 2005; Vicente, 1999). It has also been used for control systems engineering as part of the Multilevel Flow Modelling framework (Lind, 2011a), to describe control systems (Mazaeva and Bisantz, 2007), and for ecological automation design (Amelink, 2010). Further, it is used as a basis for user interface design within Ecological Interface Design (Burns and Hajdukiewicz, 2004; Jamieson et al., 2007; Vicente and Rasmussen, 1992). Abstraction hierarchies can be used to create knowledge representations (Rasmussen and Lind, 1982; Rasmussen, 1985, 1979), i.e., to represent conceptual and mental models of operators. Thus, the applicability of abstraction hierarchies spans all system parts described by the work system model presented in Figure 10.

In chapter 4, the necessary capabilities of a useful method were stated. But what does the approach actually have to tell the user about method/methodology? What kind of questions will the user of the method/methodology have to answer to improve the match between system parts? And what should be the content of an approach that matches up to established method requirements? The question matrix presented in Figure 30 suggests a set of questions based on the requirements elicitation in chapter 4. The questions can be used to help identify the content of each cell in the matrix. The questions stated in the matrix are not exhaustive. However they are an attempt to guide how the integration of levels and columns can be interpreted.

	Dynamic domain	P ⇆ CS	Control system	CS ⇆ UI	Control system user interface	UI ⇆ Op.	Operator(s)	Generic queries
Task	What tasks are possible in the domain? What is the available action space in the domain?	How is task info communicated between the domain and the control system? How does the control actions space map onto the available action space?	How does the control system contribute to task performance? What is the available action space for control?	How is sequential control system activity communicated? How is the available control abilities communicated?	How can performance of tasks be represented and supported? What is the displayed action space?	How do presented tasks correspond to the operators intentions? How is available domain and control action space communicated?	How can operators' goal related activities (tasks) be described? What is the perceived action space?	How do you have to work to achieve a given goal?
Function	What physical and abstract functions are present?	How are control functions used to shape the dynamic domain?	What functions does the control system fulfil in the dynamic domain?	How are control system functionality communicated?	How can the process and control system functions be represented?	How can responsibility be mapped between technical functions and operator roles?	What are the operators' roles in work? What is expected of operators?	What functions are available in the system?
Process	What physical processes are present?	How do process and control equipment communicate?	How do the control algorithms work?	How can the process dynamics and control loops be monitored?	How can the dynamical flow in the process and in the control system be represented?	How is operator cognition (perception, thinking, action) supported?	How can operator cognition (perception, thinking, action) be described?	How can the system's dynamic behaviour be described?
Structure	What physical objects are present?	How is data collected from the domain?	What control equipment, sensors, actuators and algorithms are present?	How is data integrated into information?	What graphical abilities are available in the control system?	How does the operator perceive the graphics? How are affordances realised in graphics?	What are the operators' profile and characteristics?	What does the system look like physically?
Generic queries	How are the goals of the work domain achieved?	How does the CS shape the dynamic domain?	How does the control system work?	What control signals are given? What data is retrieved from the CS?	What information and which controls are available?	What intentions and expectations will the operator(s) express through action? What info is given from the HMI?	What knowledge is required by the operator(s)?	

Figure 30. Question matrix

5.2 Description of the System Representation Matrix

The method will be presented and explained in three steps.

1. The structure of the matrix
2. How to use the system representation for analysis
3. Iterative procedure for creating a system representation within the matrix

First the structure of the matrix template is described and an example of a system representation within the matrix is presented. Second, examples are given of how narratives charted in the system representation can be used to analyse operations. Third, a systematic and iterative procedure for building the system representation is presented.

Throughout the method description, a home appliance product, a toaster, will be used as a guiding example. Then, a paint factory simulator is analysed as an example of a system with a higher degree of complexity.

5.2.1 The structure of the System Representation Matrix

The Matrix

The matrix consists of four levels and five columns. The four levels describe the work system from different levels of abstraction. The columns describe the work system from the contextual, technological and cognitive perspective. Each cell in the matrix is a container that represents an aspect of the work system. In Figure 30 each cell is explained by a query that, when answered, will elucidate an aspect of the system. The questions given here are examples; each cell in the matrix can be elaborated to the extent needed for a particular analysis.

Table 10. Question matrix with questions

	A. Context	B. Main system	C. Control
1. Task	Domain purpose What is the purpose of the work system?	Domain tasks What tasks are possible to perform in the work system? What tasks are necessary to achieve the domain purpose?	Control of tasks How is task performance controlled?
2. Function	Domain values What values and priorities are present in the work system?	Physical functions What physical functions are necessary in the work system?	Control functions What control functions are necessary in the work system?
3. Process	Laws of nature What laws of nature are of importance in the work system?	Object related processes What physical processes are present in the work system?	Control of processes How do the control system's algorithms work?
4. Structure		Physical objects What physical objects are present in the work system?	Control of objects What control equipment, sensors, algorithms and actuators are present in the work system?

Table 10. continued from previous page

D. User interface		E. Knowledge
Information	Action	
Task related information How are tasks represented and supported?	Action opportunities How can tasks be performed in the interface?	Knowledge of tasks What task related knowledge does the user need to have?
Information on functional relationships How are the values, the physical functions and the control functions represented in the interface?	Means to change functions How can functions be activated or altered by means of the interface?	Knowledge of functional relationships What function related knowledge does the user need to have?
Process related information How is the main system and control system processes represented in the interface?	Means to change processes How can processes be activated or altered by means of the interface?	Knowledge of processes What process related knowledge does the user need to have?
Object related information How is the physical structure represented in the interface?	Means to change the physical structure What are the physical means for action in the interface?	Knowledge of the physical structure What structure related knowledge does the user need to have?

Columns

The columns from left to right are: Context, Main system, Control, User interface, and Knowledge. The columns represent different parts of the human-machine system under analysis.

- The Context column describes how the environment affects the activity performed in the human-machine system.
- The Main system column represents the technical core of the producing work system.
- The Control column represents the control functions used to observe and direct the Main system.
- The User interface column represents how the system is interfaced with the human. The User interface column is divided into two sub-columns; Information and Action. The Information column represents the information provided by the technical system, while the Action column represents the actions available and that the control system offers to the operator.
- The Knowledge column represents the accumulated knowledge needed to understand the system as a whole. The necessary knowledge is defined by the content found in the Context, Main system, Control and User interface.

In the toaster example, the Context column reflects the social and natural environment in which the toaster operates. The Main system, Control and User interface columns represent the toaster itself, while the Knowledge column represents the user's inherent knowledge of both the toaster and its environment.

Levels

The levels from top to bottom are Task, Function, Process and Structure.

- The Task level represents what has to be physically or cognitively performed by humans or machines in the work system.
- The Function level represents the physical and abstract functionality necessary for the work system to fulfil its purpose.
- The Process level represents the flow of energy, material and information found in the work system.
- The Structure level represents the physical objects found in the work system.

To give an example, we can start from the bottom of the hierarchy, where the *Structure* represents the physical objects present in the work domain, and how these objects are connected physically to each other. For example, in a toaster there are physical components such as metal casing, a spring-loaded tray, nichrome wiring, timer, etc. The *Process* level represents what happens when using the objects in the physical structure. In a toaster, the *Process* can be exemplified by the electric current generating infrared radiation, and that toasts the bread. The *Function* level represents the reasons why the process and structure exist. For example, the toaster provides a heating function. The *Task* level represents what is being performed in the work domain to reach the intended goals. To perform tasks, the operator uses the available functions to adjust or create a process by interacting with the physical objects in the domain. In the toaster example, the task consists of e.g. placing a slice of bread in the tray, adjusting the heat-knob and pushing the handle to start toasting. Table 11 shows an example where each question is answered. Table 11 is an example of an existing artefact being analysed. If the purpose is to design new technology, the answers would relate to how the work system could function, rather than to how it is functioning.

Table 11. System Representation Matrix with answers

	A. Context	B. Main system	C. Control
1. Task	What is the purpose of the work system? *To produce toast.*	What tasks are possible to perform in the work system? What tasks are necessary to achieve the domain purpose? *E.g. place bread, adjust toast level, press handle, toasting, remove bread.*	How is task performance controlled? *E.g. decision of toast level, start heating, checking toast colour, decision to stop heating.*
2. Function	What values and priorities are present in the work system? *To produce toast with perfect colour and crunchiness.*	What physical functions are necessary in the work system? *E.g. hold bread in position, produce heat, adjust time.*	What control functions are necessary in the work system? *E.g. control of the circuit breaker.*
3. Process	What laws of nature are of importance to the work system? *E.g. electricity, ohmic heating, breaking of molecular bonds*	What physical processes are present in the work system? *E.g. flow of electrical current, heat conversion, absorption of energy.*	How do the control system's algorithms work? *E.g. charge the capacitor, when charged this cuts the power, which releases the electromagnet and the bread pops up.*
4. Structure		What physical objects are present in the work system? *E.g. casing, heating circuit, mica plate, spring loaded tray.*	What control equipment, sensors, algorithms and actuators are present in the work system? *E.g. timer circuit*

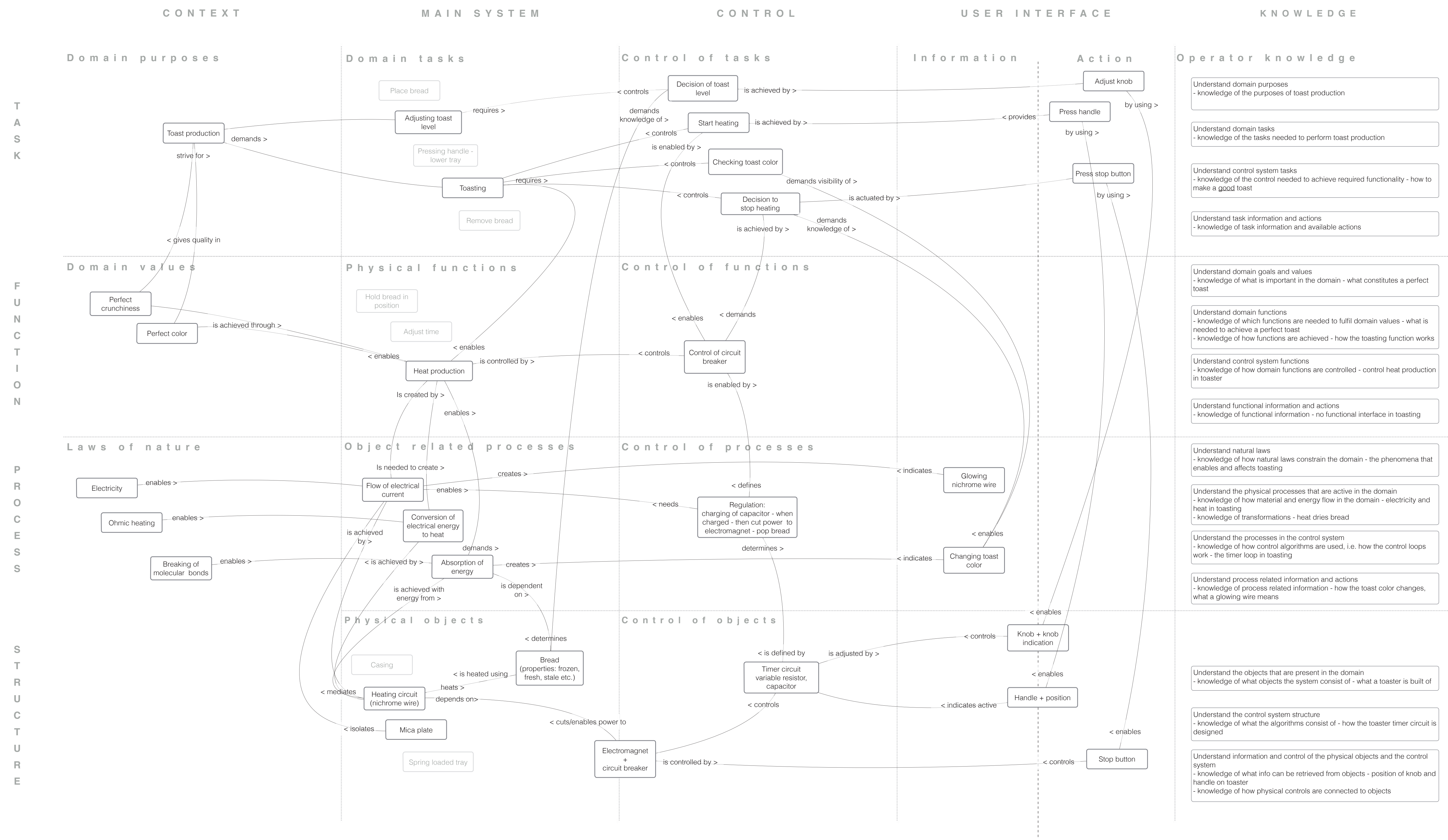
Table 11. continued from previous page

D. User interface		E. Knowledge
Information	Action	
How is performance of tasks represented and supported? *E.g. by reading toaster manual*	How can tasks be performed in the interface? *E.g. press handle, press stop button.*	What task related knowledge does the user need to have? *E.g., the tasks involved in producing toast, what decisions have to be made, etc.*
How are the values, the physical functions and the control functions represented in the interface? -	How can functions be activated or altered by means of the interface? -	What function related knowledge does the user need to have? *Understanding of the relationship between entities to provide quality.*
How are the main system and control system processes represented in the interface? *E.g. glowing nichrome wire and changing toast colour.*	How can processes be activated or altered by means of the interface? -	What process related knowledge does the user need to have? *E.g., knowledge of how the bread will change its colour.*
How is the physical structure represented in the interface? *E.g. position of handle and indication on toast level knob.*	What are the physical means for action in the interface? *E.g. handle and toast level knob.*	What structure related knowledge does the user need to have? *E.g., knowledge of what the toaster looks like*

Relations between cells

The relations cannot be captured in the tabular format. In Figure 31 the matrix in Table 11 is further developed to make the relations between entities visible. Note how the answers from the matrix are found in the boxes. To keep the example fairly brief, the system representation has not been fully developed. The grey boxes without relations indicate there are more entities that could be included. The relations between boxes are drawn with lines and each relation is described by a word pair. The relations can be of different kinds, for example means-ends, control or information relationships.

One challenge in making the system representation is the complexity that arises as entities and relations are drawn. Therefore an important purpose of the analysis is to state this early on, so the analysis can be delimited and focused on parts of interest. To deal with and represent the complexity is also a matter of visualisation technique.



CONTEXT
MAIN SYSTEM
CONTROL
USER INTERFACE
KNOWLEDGE
TASK
FUNCTION
PROCESS
STRUCTURE
Domain purposes
Domain tasks
Control of tasks
Information
Action
Operator knowledge
Place bread
Toast production
demands >
strive for >
Adjusting toast level
requires >
Pressing handle - lower tray
Toasting
requires >
Remove bread
< gives quality in
< controls
Decision of toast level
is achieved by >
Adjust knob
by using >
demands knowledge of >
Start heating
is achieved by >
< provides
Press handle
by using >
< controls
is enabled by >
Checking toast color
< controls
demands visibility of >
Press stop button
by using >
< controls
Decision to stop heating
is actuated by >
is achieved by >
demands knowledge of >
Understand domain purposes
- knowledge of the purposes of toast production
Understand domain tasks
- knowledge of the tasks needed to perform toast production
Understand control system tasks
- knowledge of the control needed to achieve required functionality - how to make a good toast
Understand task information and actions
- knowledge of task information and available actions
Domain values
Physical functions
Control of functions
Perfect crunchiness
Perfect color
is achieved through >
< enables
Hold bread in position
Adjust time
< enables
Heat production
is controlled by >
< controls
Control of circuit breaker
< enables
< demands
is enabled by >
Is created by >
enables >
Understand domain goals and values
- knowledge of what is important in the domain - what constitutes a perfect toast
Understand domain functions
- knowledge of which functions are needed to fulfil domain values - what is needed to achieve a perfect toast
- knowledge of how functions are achieved - how the toasting function works
Understand control system functions
- knowledge of how domain functions are controlled - control heat production in toaster
Understand functional information and actions
- knowledge of functional information - no functional interface in toasting
Laws of nature
Object related processes
Control of processes
Is needed to create >
Electricity
enables >
Flow of electrical current
creates >
< indicates
Glowing nichrome wire
enables >
< defines
Ohmic heating
enables >
Conversion of electrical energy to heat
< needs
Regulation: charging of capacitor - when charged - then cut power to electromagnet - pop bread
is achieved by >
demands >
determines >
< enables
Breaking of molecular bonds
enables >
< is achieved by >
Absorption of energy
creates >
< indicates
Changing toast color
is achieved with energy from >
is dependent on >
Understand natural laws
- knowledge of how natural laws constrain the domain - the phenomena that enables and affects toasting
Understand the physical processes that are active in the domain
- knowledge of how material and energy flow in the domain - electricity and heat in toasting
- knowledge of transformations - heat dries bread
Understand the processes in the control system
- knowledge of how control algorithms are used, i.e. how the control loops work - the timer loop in toasting
Understand process related information and actions
- knowledge of process related information - how the toast color changes, what a glowing wire means
Physical objects
Control of objects
< enables
< determines
Casing
Bread (properties: frozen, fresh, stale etc.)
< is heated using
< is defined by
is adjusted by >
< controls
Knob + knob indication
< mediates
heats >
Heating circuit (nichrome wire)
depends on>
Timer circuit variable resistor, capacitor
< enables
Handle + position
< indicates active
< controls
< isolates
Mica plate
< cuts/enables power to
< enables
Electromagnet + circuit breaker
is controlled by >
< controls
Stop button
Spring loaded tray
Understand the objects that are present in the domain
- knowledge of what objects the system consist of - what a toaster is built of
Understand the control system structure
- knowledge of what the algorithms consist of - how the toaster timer circuit is designed
Understand information and control of the physical objects and the control system
- knowledge of what info can be retrieved from objects - position of knob and handle on toaster
- knowledge of how physical controls are connected to objects

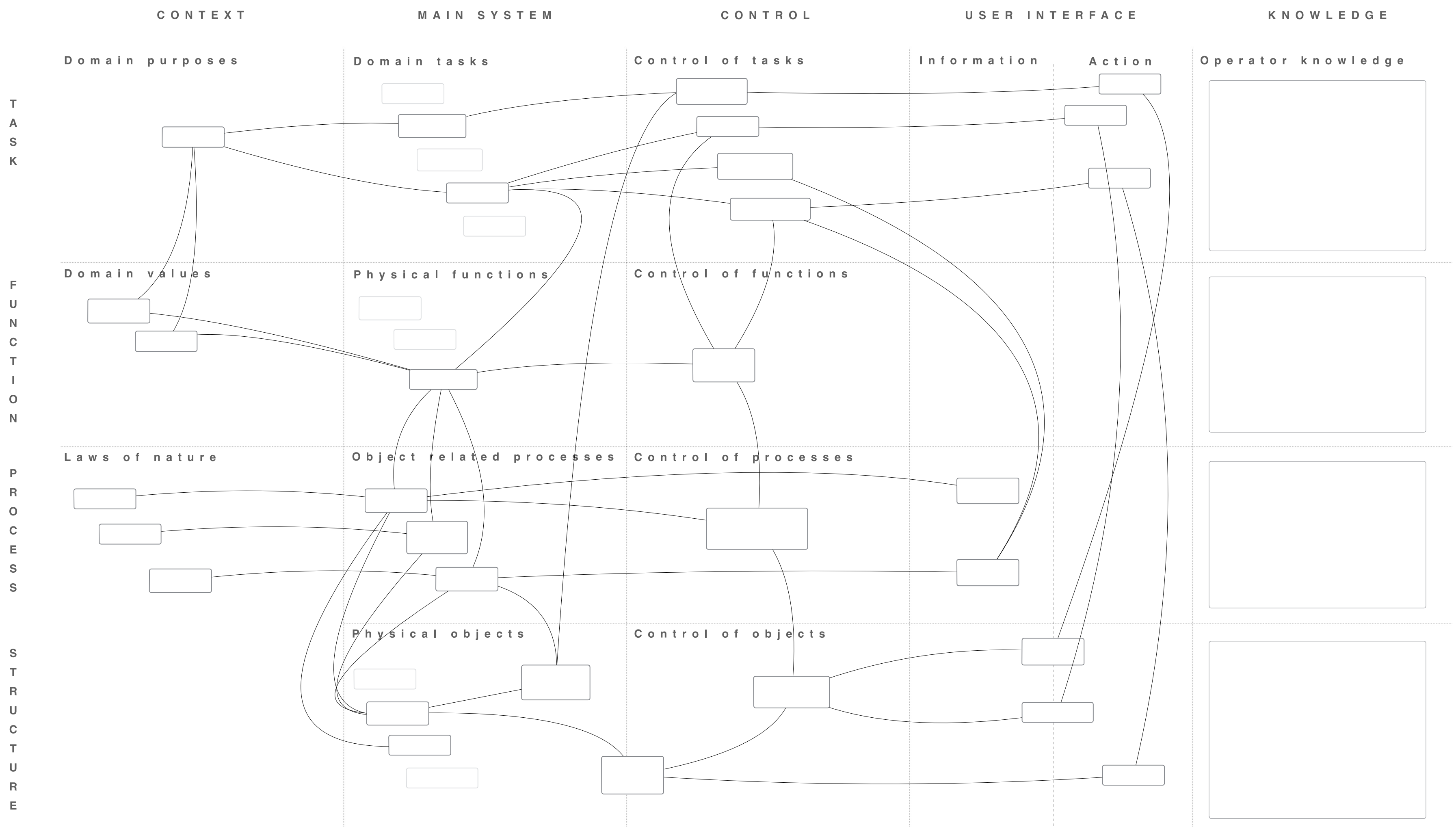


Figure 31. The toaster described in the System Representation Matrix (boxes are intentionally blank)

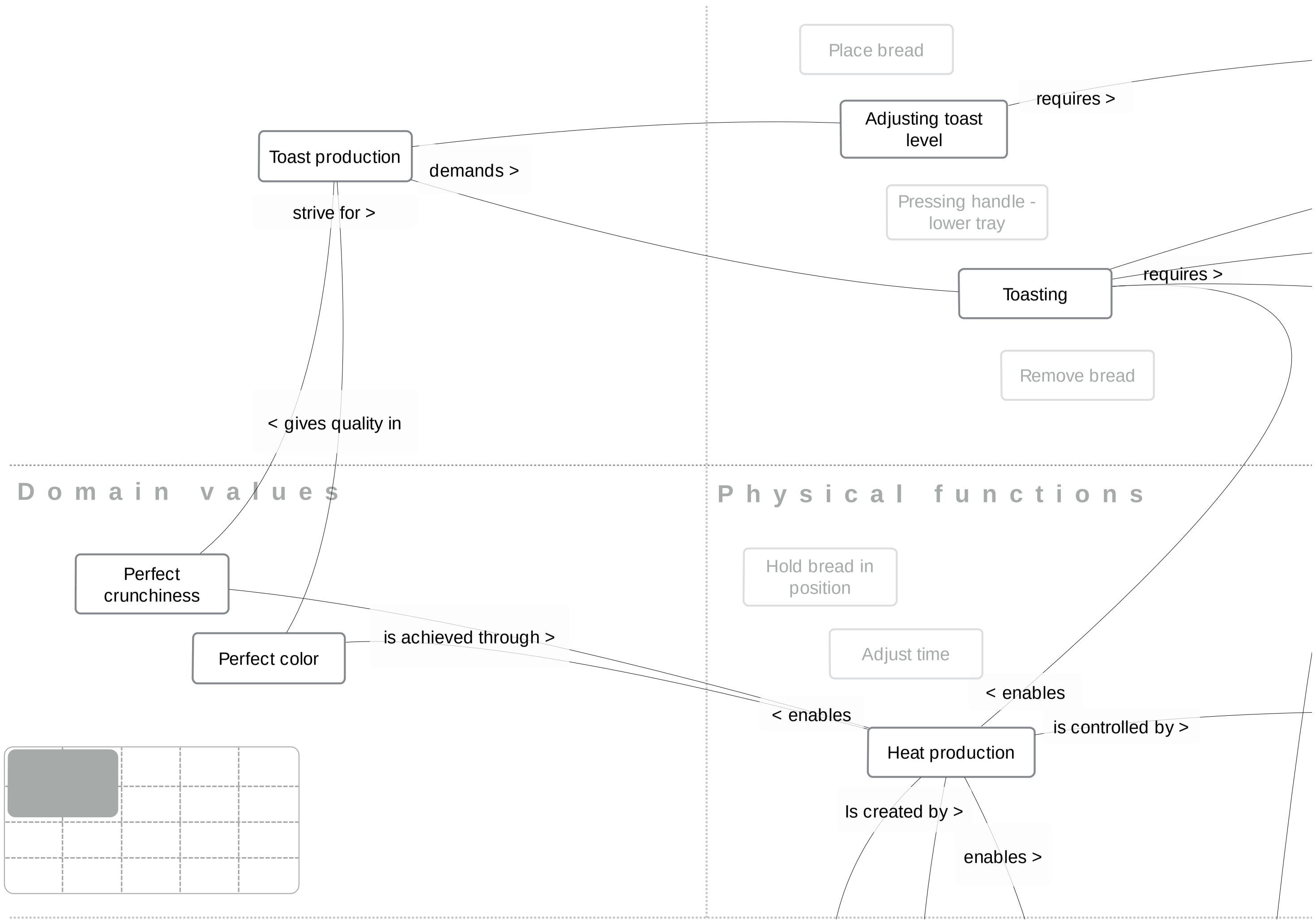


Figure 32. Upper left quadrant of the toaster system representation matrix

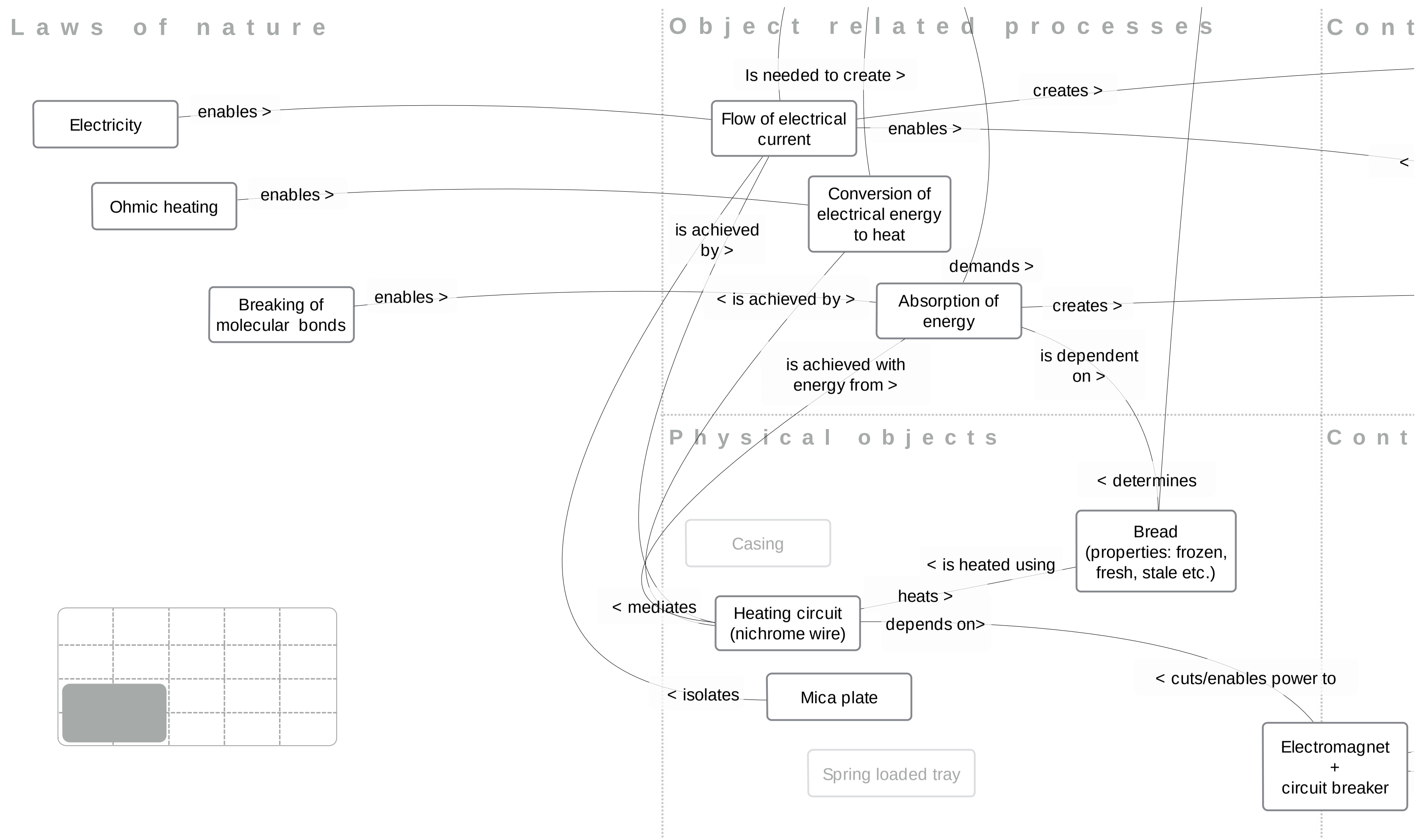


Figure 33. Lower left quadrant of the toaster system representation matrix

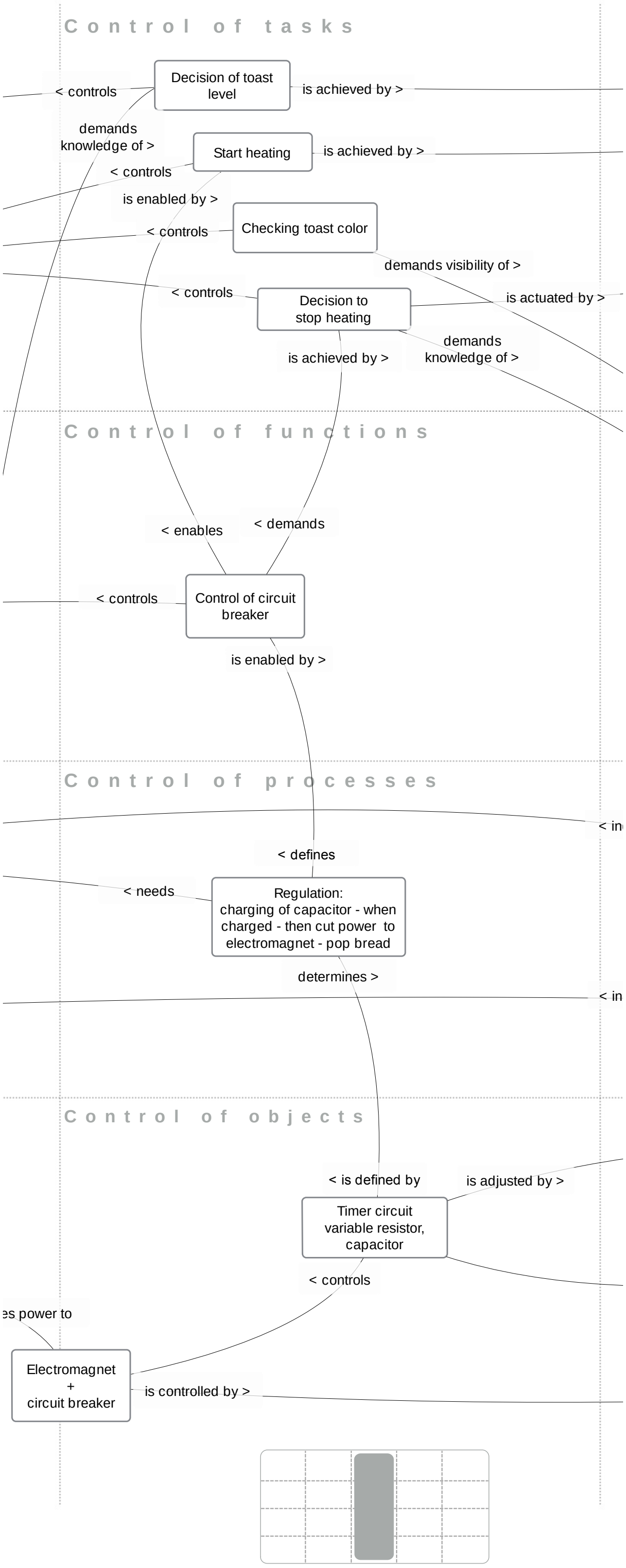


Figure 34. Control column of the toaster system representation matrix

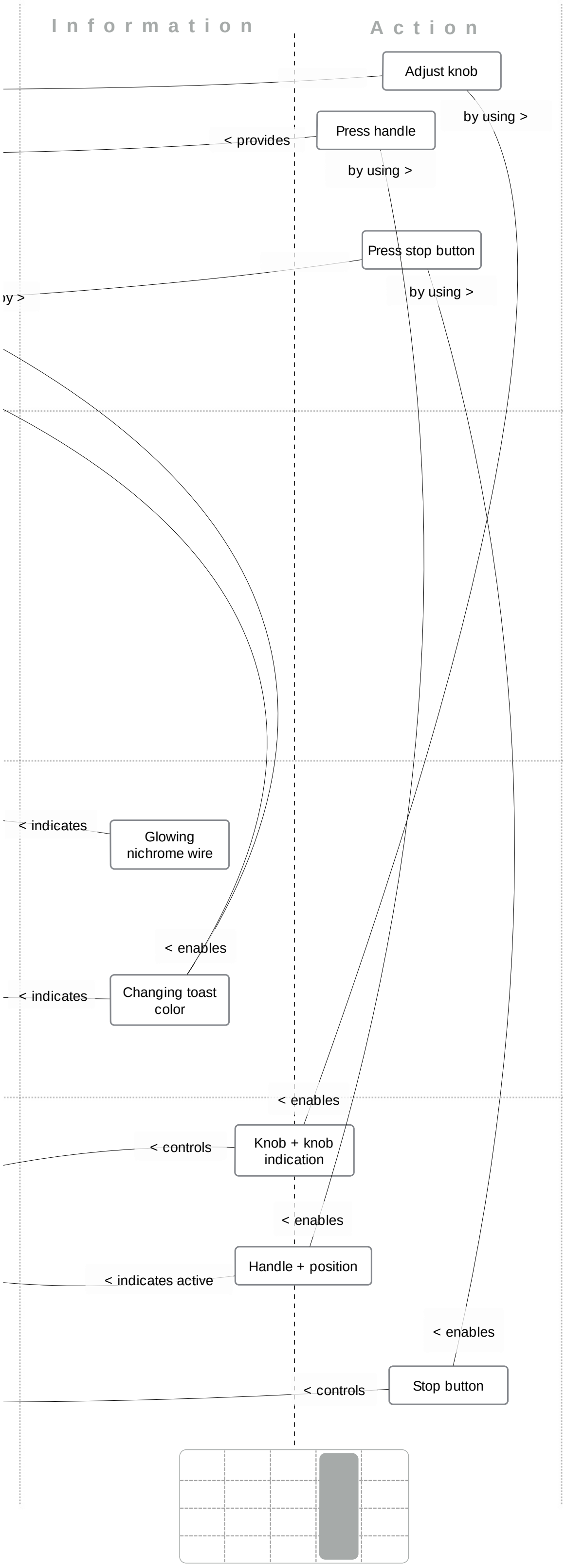


Figure 35. Interface column of the system representation matrix

Task
Understand domain purposes - knowledge of the purposes of toast production
Understand domain tasks - knowledge of the tasks needed to perform toast production
Understand control system tasks - knowledge of the control needed to achieve required functionality - how to make good toast
Understand task information and actions - knowledge of task information and available actions

Function
Understand domain goals and values - knowledge of what is important in the domain - what constitutes perfect toast
Understand domain functions - knowledge of which functions are needed to fulfil domain values - what is needed to achieve perfect toast - knowledge of how functions are achieved - how the toasting function works
Understand control system functions - knowledge of how domain functions are controlled - control heat production in toaster
Understand functional information and actions - knowledge of functional information - no functional interface in toasting

Process
Understand natural laws - knowledge of how natural laws constrain the domain - the phenomena that enables and affects toasting
Understand the physical processes that are active in the domain - knowledge of how material and energy flow in the domain - electricity and heat in toasting - knowledge of transformations - heat dries bread
Understand the processes in the control system - knowledge of how control algorithms are used, i.e. how the control loops work - the timer loop in toasting
Understand process related information and actions - knowledge of process related information - how the toast colour changes, what a glowing wire means

Structure
Understand the objects that are present in the domain - knowledge of what objects the system consist of - what a toaster is built of
Understand the control system structure - knowledge of what the algorithms consist of - how the toaster timer circuit is designed
Understand information and control of the physical objects and the control system - knowledge of what info can be retrieved from objects - position of knob and handle on toaster - knowledge of how physical controls are connected to objects

Figure 36. Knowledge column of the toaster representation matrix

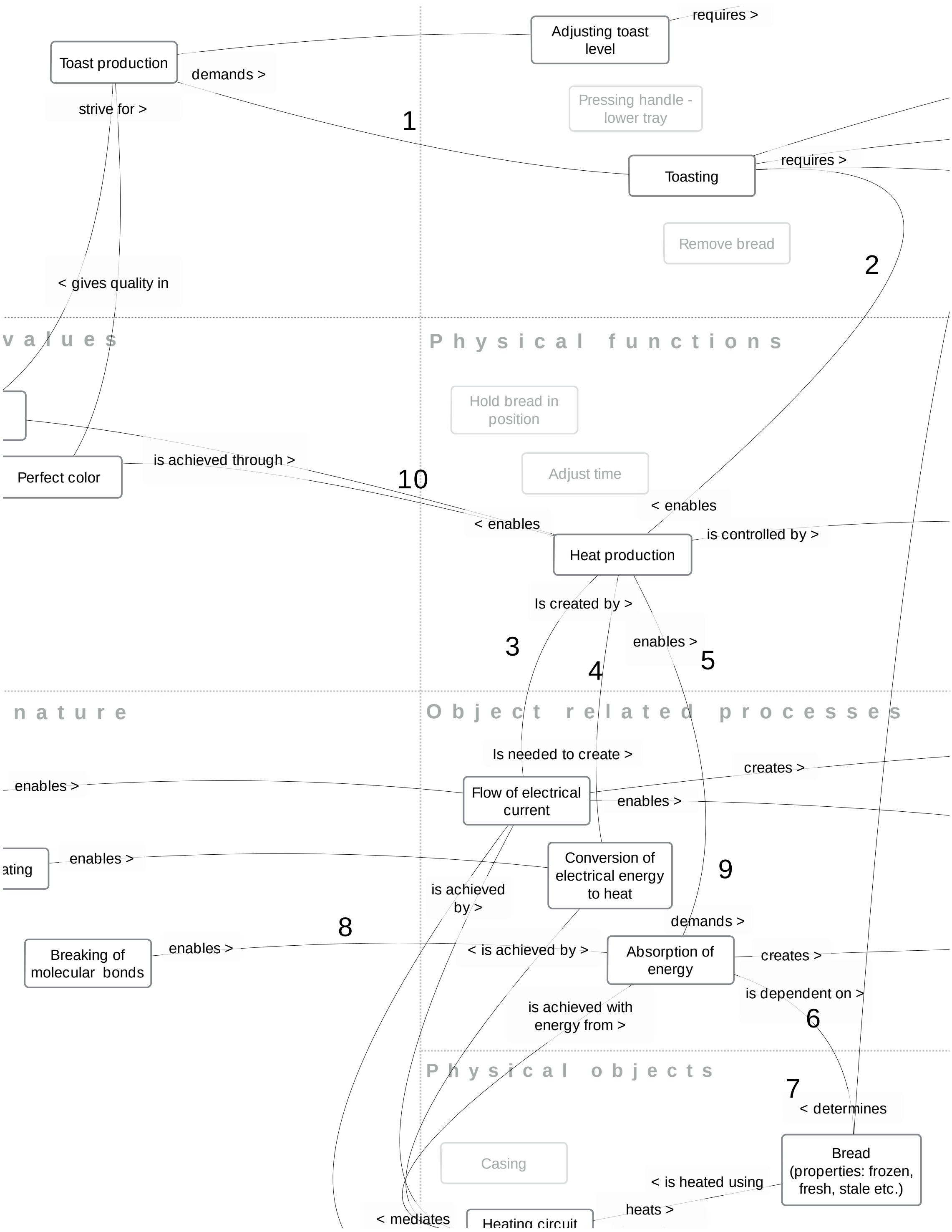


Figure 37. Reading the system representation (part of Figure 31)

Figure 37 is an example of how the system representation can be read. The representation resembles a concept map (Novak and Cañas, 2008) that can be read in natural language. To clarify how the system representation can be read, we can start in the domain purpose cell. The steps can be followed by the numbers in Figure 37. A part of the system representation can be read as follows: To fulfil the purpose of toast production we need to perform the toasting task (1). The toasting task requires heat production (2). Heat production in a toaster is created by the flow of electrical current (3) together with the process of converting electrical energy to radiation (4), i.e., heat. Heat production enables absorption of energy (5), and this absorption is dependent on the bread properties (6), e.g. if it is frozen, fresh or stale. The bread properties also determine how much and how energy is absorbed (7). The absorption of energy is achieved by breaking molecular bonds (8), and the absorption of energy demands heat production (9). Heat production enables the achievement of good toast, i.e., reaching the values of perfect crunchiness and colour (10).

The example only includes two of the columns, but the whole system representation can be read in a similar way. The only entities not connected by relations, are those found in the operator knowledge column. Since knowledge acquisition depends on how the technical system is designed, the knowledge entities summarise each cell in the matrix. To improve the clarity of the system representation, the aggregate knowledge demand is collected in the operator knowledge column without connecting lines. Knowledge demands are, however, collected from every entity and relation in the system representation.

5.3 How to use the matrix for analysis

System narrative
The system representation matrix can be used for analysis by creating a system narrative. The system narrative is an interpretation of the system representation and a way of giving the representation a meaning. One way to create a narrative is to ask a question (from real experience or imagined) and map the reasoning on to the system representation. By doing so, the prerequisites for successful system performance can be analytically evaluated.

Figure 38 and Figure 39 provide examples of how a system narrative can be mapped onto the system representation. The question asked in this case is "*What are the prerequisites for successful toast production?"* Two domain tasks related to the purpose of producing toast are developed further in the system representation, *Adjusting toast level* and *Toasting.*

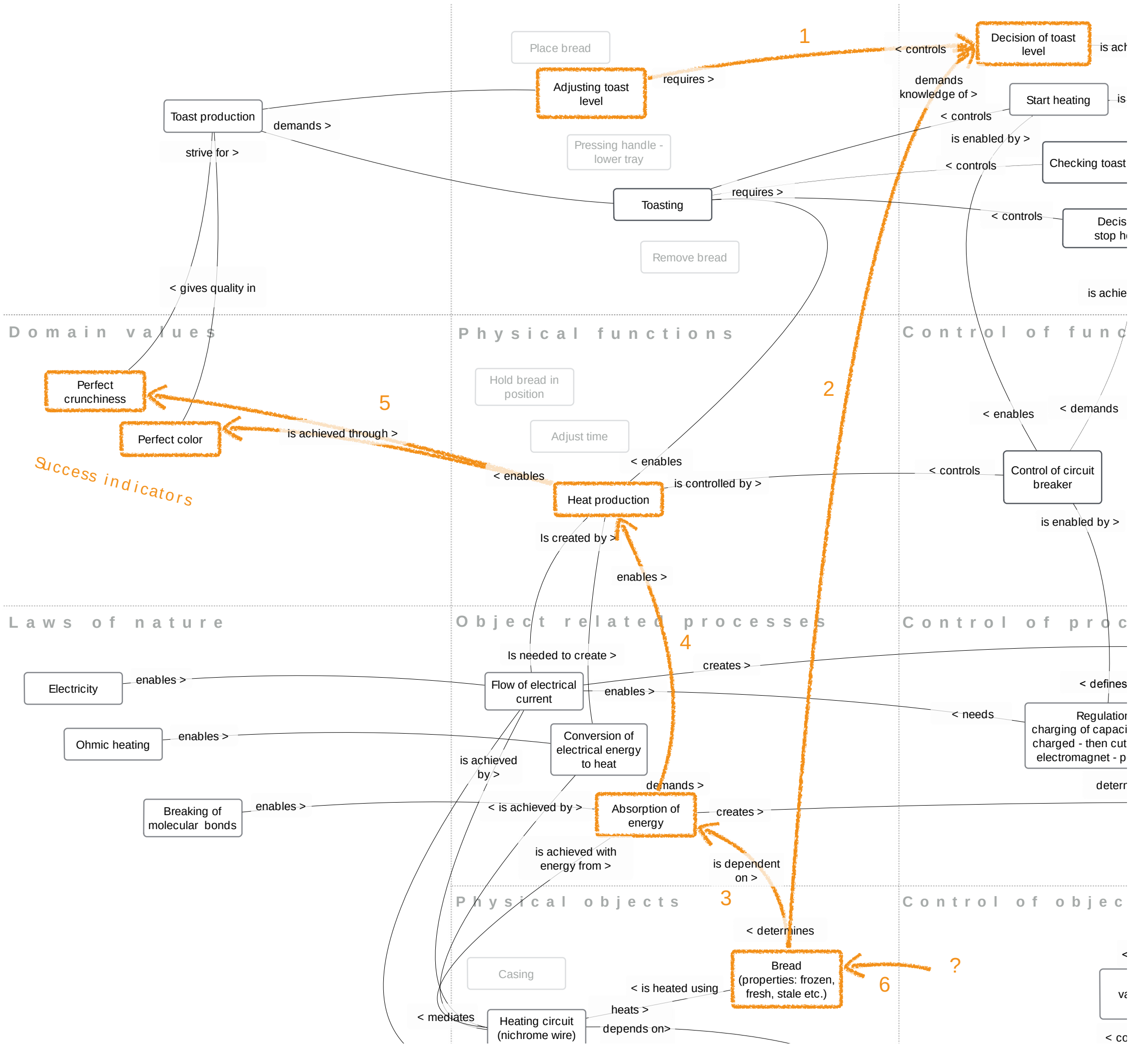


Figure 38. Example of interpretation of the System Representation Matrix of a toaster

Figure 38 shows an example of how the System Representation Matrix of a toaster can be interpreted. The numbers in the text refer to the numbers in Figure 38. To adjust the toast level, a decision about toast level has to be made (1). The appropriate toast level is dependent on the properties of the bread (2). The properties of the bread determine how much energy has to be absorbed (3) when heated (4) to reach the desired qualities of perfect colour and crunchiness (5). However, no measurement of the bread properties exist (6), which means the machine cannot determine, and adjust to obtain, the appropriate toast level. Instead, the user has to make this judgement based on physical senses and experience from earlier toasting sessions. A knowledge demand is thereby imposed on the user.

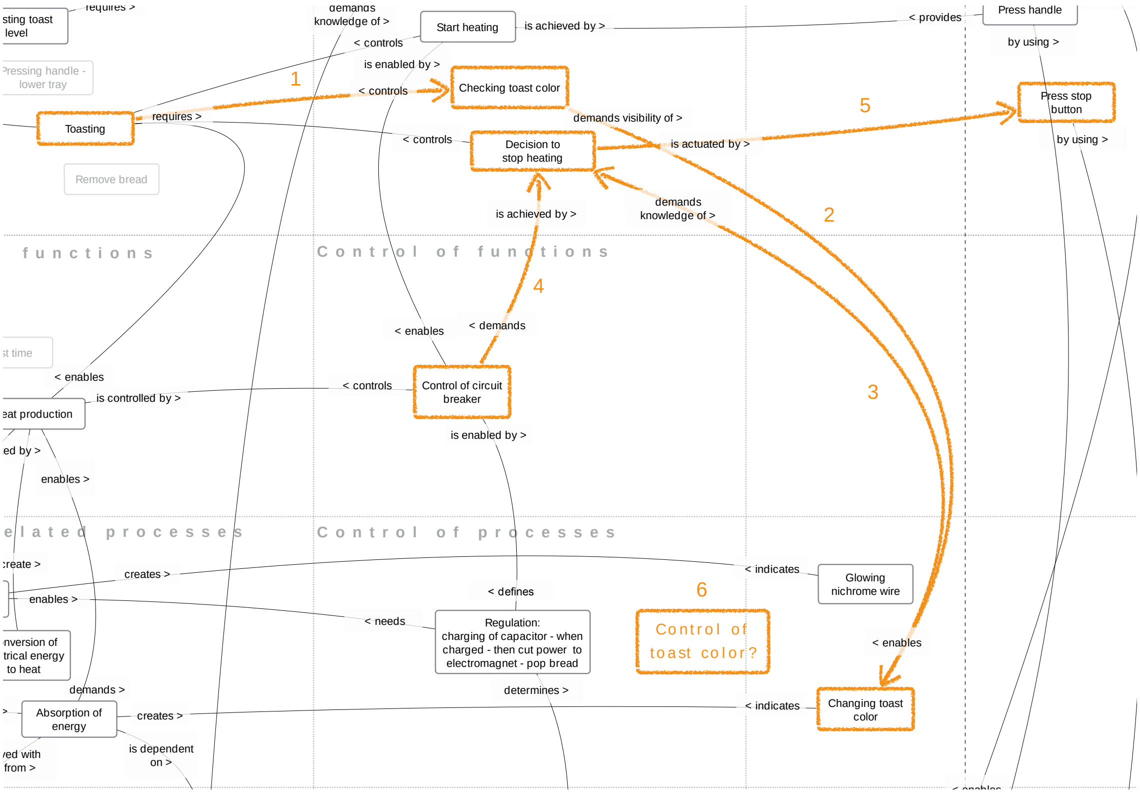


Figure 39. Example of interpretation of the System Representation Matrix of a toaster

Figure 39 shows another example. To perform the toasting task efficiently, there are three control tasks involved, where checking toast colour (1) is of primary importance in fulfilling domain values. The colour check demands visibility of the colour change (2), which in turn enables a decision as to when to stop heating (3). The decision to stop heating can be made both by the machine (based on toast level setting) (4) and by the operator pressing the stop button (5). The toast colour is however, not included in the control loop of the machine, since there is no sensor and no algorithm included in the technical system (6).

The conclusion regarding the prerequisites for successful toast production, based on the analysis of the system representation, is that manual operation will probably be more successful. Since the automatic control of the time the heating function is active has no connection to bread properties, there is a probability of the bread absorbing too much energy and becoming burnt. A poor control strategy has thus been discovered, and ideas for improvement can be derived from the analysis (e.g., improve sensing). Based on the knowledge demands, we could make a qualified guess that the user will adapt to machine limitations by learning from how bread with different properties behaves, but at the cost of trial and error. The toaster narrative provides two very brief examples of how representation can be applied for reasoning about system functioning in different situations.

5.3.1 How the System Representation Matrix can aid achieving representational matches

There are other opportunities for how system representation can be used in analysis and design of human-machine systems. As has already been indicated, the method can be used to determine required operator knowledge for system understanding. By describing the knowledge that resides in the system (e.g., the designers' intention and the actual functioning) it can be assessed what knowledge the operator requires to accomplish different roles. When the required knowledge is known it is possible to create an operator profile and specify needs for training and education. This will help achieve representational matches between the operator and other parts of the joint system (Figure 23).

Further, the system representation can be used as an aid when specifying information needs and user interface requirements. When a system representation providing a description of the work system has been created, the entities and relations in the system representation can be used as a basis for information needs specification. Once the needs have been established, the specific user interface requirements can be implied from these needs. By using principles of task-based, ecological-, functional- and standard process oriented design a comprehensive set of design tools can be used to create a graphic representation of the work system. By using the system representation as a basis for specifying the information content of a control system user interface the system representation matrix contributes to improve the representational match between the user interface, the control system, and the dynamic domain. As was described in chapter 3.1, achieving representational matches can also be assumed to reduce the possible problems in automated human-machine systems.

In chapter 6.1.3 the representation of gaps and matches will be further explored. It will be shown how the System Representation Matrix can be used to represent human-automation related challenges in a paint factory batch process simulator. First it is described how a System Representation Matrix can be created by using a step-by-step procedure.

5.4 How to create a System Representation Matrix

System representation is built by iterating between three steps: (A) identifying entities, (B) establishing relations and (C) creating a system narrative.

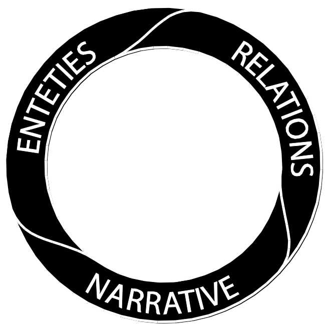


Figure 40. System representation is built by iteratively moving between three phases: Identifying entities, Describing relations, and Creating a system narrative.

Step A, identifying entities, is done by answering the question matrix (see Table 11). By identifying entities in the work system and categorising them into a matrix cell, the work system can be described in terms of what it contains. The questions proposed in Figure 30 are an aid to identifying these physical and abstract entities.

Step B, establishing relations, is made by describing the existing relationship between the system entities identified in phase A. This can be done graphically, by drawing a system representation.

Step C, creating a system narrative, is a way of lending the system representation a meaning through interpretation. A system narrative, e.g. an imagined scenario or story from operational settings, can function as a starting point for mapping out system functions.

In practice, the three phases could be performed in any order; for example, a narrative (e.g. a story or description of a scenario or situation based on operational experience) could lead to identification of new entities. Going through any of the steps, continuous revision of the system should be expected.

The development of the system representation is an iterative process, and as a model it will always be a simplification of reality, hence it will always be possible to both extend and elaborate the system representation into more detail. The decision as to when the representation is good enough, has to be based on a pragmatic judgement in relation to how the system representation should be used, i.e. is it useful when trying to find answers to questions asked in the process of analysis or design?

5.4.1 A systematic procedure to populate the System Representation Matrix

From the evaluation (presented in chapter 6) it was concluded that a systematic description of how to use the method is necessary to guide novice users. By focusing on one smaller part of the matrix at a time, representation can be built systematically. In Table 12 a systematic procedure to populate the System Representation Matrix is suggested. Table 12 shows one way of doing this, and there are most certainly other ways to go about the procedure. I encourage the inquisitive practitioner to find the way most suitable in any given context. In practice, the matrix can be expected to be populated more iteratively than described in the tabular format, as entities and relations are discovered. The intention of the procedure in Table 12 is to provide a pedagogical entrance to using the method. Figure 41 shows the matrix to make it easier to follow the systematic procedure.

	A	B	C	D	E
1	A1	B1	C1	D1	E1
2	A2	B2	C2	D2	E2
3	A3+4	B3	C3	D3	E3
4		B4	C4	D4	E4

Figure 41. Matrix orientation

Table 12. A systematic procedure to populate the matrix

Step 1. Define the scope of analysis

The first step of using the System Representation Matrix is to determine the scope of the analysis. Scope can be defined by questions to which the analyst seeks an answer. Formulating the questions will help delimit and focus analysis activity.

Step 2. Upper left quadrant

Cell	
A1	Start with defining and listing the purposes of the system
B2	List the functions necessary to fulfil the system purposes
A2	Define the values and priorities that can be used to estimate the system performance
	Connect A1 and B2 via A2 and define how the entities are related
B1	Define the tasks that have to be performed by using the functions to achieve the system purposes
	Connect A1 and B2 via B1 and define how the entities are related

Step 3. Lower left quadrant

B4	List the physical objects that the system consists of
B3	Define the processes needed for the objects to fulfil the functions
	Connect B2 and B4 via B3 and define how the entities are related
A3+4	List the laws of nature of relevance to the current analysis
	Connect A3+4 with B3 and B4 and define how the entities are related

Step 4. Control column

C2	List the control functions necessary to the work system
C3	Based on the control functions in C2, define control processes
C4	List the control equipment necessary to fulfil the control functions
	Connect C2 and C4 via C3 and define how the entities are related
	Connect C2-C4 with B2-B4 and define how entities are related
C1	List the control tasks involved in achieving the domain task (B1)
	Connect C1 with B1 and C2 and define how entities are related

Step 5. Interface column

D1	List the action opportunities and task related information in the interface
D2	Describe how the entities in A2, B2 and C2 are represented in the interface List the means for action in the interface related to A2, B2 and C2
D3	Describe how the entities in A3, B3 and C3 are represented in the interface List the means for action in the interface related to A3, B3 and C3
D4	Describe how the entities in A3, B3 and C3 are represented in the interface List the means for action in the interface related to A3, B3 and C3

Step 6. Knowledge column

In the knowledge column, knowledge demands are derived based on system representation. By deriving knowledge demands from each cell in the matrix, an aggregated image of required knowledge is defined.	
E1	Describe the knowledge demand based on entities and relations from row 1
E2	Describe the knowledge demand based on entities and relations from row 2
E3	Describe the knowledge demand based on entities and relations from row 3
E4	Describe the knowledge demand based on entities and relations from row 4

5.4.2 The systematic procedure applied in the toaster example

The stepwise procedure presented in Table 11 will now be exemplified using the toaster as an example.

Step 1. System boundaries
The system boundaries in the example are the toaster and the user of the toaster.

Step 2: Upper left quadrant (Figure 32)
A1: The purpose of the system is to produce toast.
B2: Toasting is achieved by heat production.
A2: Successful toasting is identified by perfect colour and crunchiness of the bread.

Relations: A1-B2 via A2
- Toast production strives for perfect colour and crunchiness.
- Perfect colour and crunchiness indicates quality in toast production.
- Perfect colour and crunchiness are achieved through heat production.
- Heat production enables perfect colour and crunchiness.

B1: Two tasks that have to be performed to achieve toast production are Adjust the Toast Level and perform the Toasting.

Relations: A1-B2 via B1
- Toasting requires heat production
- Heat production enables toasting

Step 3: Lower left quadrant (Figure 33)
B4: The physical objects included in the analysis are the heating circuit, the mica plate, the electromagnet with circuit breaker, and the bread
B3: The physical processes involved in toasting are: flow of electrical current, conversion of electrical energy to heat, and absorption of energy.

Relations: B2-B4 via B3
- Flow of electrical current is needed to create heat production. Flow of electrical current is achieved by the heating circuit and the mica plate. The heating circuit mediates flow of electrical current.
- The conversion of electrical energy to heat is achieved by the heating circuit. The heating circuit mediates the conversion of electrical heat to energy. Conversion is needed to create heat production.
- Absorption of energy demands heat production. Heat production enables absorption of energy. Absorption of energy is achieved with energy from the heating circuit. Absorption of energy is dependent on bread properties.
The electro magnet and circuit breaker enables power to the heating circuit. The heating circuit depends on the circuit breaker.

A3+4: Basic energy functions that are closely related to laws of nature involved in toasting are electricity, ohmic heating, and breaking of molecular bonds.

Relations: A3+4 with B3+B4
- Electricity enables flow of electrical current.

- Ohmic heating enables conversion of electrical energy to heat
- Breaking of molecular bonds enables absorption of energy, and absorption of energy is achieved by breaking molecular bonds

Step 4: Control column (Figure 34)
C2: The main control function is control of the circuit breaker.
C3: The control process consists of a regulation loop where a capacitor is charged; when charged this breaks the power to the electromagnet, whereby the circuit is broken and the bread pops out of the toaster.
C4: The control of objects is performed by the components in the timer circuit, together with the electromagnet and circuit breaker.

Relations: C2-C4 via C3
The control of the circuit breaker is enabled by the regulation. The regulation defines the control of the circuit breaker. The regulation determines how the timer circuit performs. The timer circuit is defined by the regulation.

Relations: C2-C4 to B2-B4:
Control of the circuit breaker controls heat production. Regulation needs flow of electrical current. The timer circuit controls the electromagnet and circuit breaker.

C1: Toasting involves a number of control tasks: decision of toast level, decision to start heating, checking of toast colour and decision to stop heating.

Relations: C1-B1
Decision of toast level controls the adjustment of toast level. Adjusting the toast level requires a decision about toast level.
Start heating, checking toast colour and the decision to stop heating, controls the actual toasting. Toasting requires heating to start, checking of toast colour and a decision to stop heating.

Relations: C1-C2
The decision of toast level demands knowledge of the bread properties.
To start heating is enabled by control of the circuit breaker.
The decision to stop heating is achieved by control of the circuit breaker (when this is activated automatically by the toaster).

Step 5: Interface column (Figure 35)
D1: The action opportunities in the toaster interface are: adjust knob, press handle and press stop button.
D2: The quality measures, the heat production function or the control of the circuit breaker are not represented in the toaster interface.
D3: The processes in the toaster can be perceived by looking at the glowing nichrome wire, or by seeing how the toast changes colour.
D4: The knob and the knob indication represents that the heating and timer circuit can be controlled. The stop button represents that the circuit can be controlled.

Relations:
The decision of toast level is realised by adjusting what is done by using the knob and the knob indication.

To start heating is achieved by pressing the handle and the handle position then indicates that the timer circuit is active.
The decision to stop toasting is realised by pressing the stop button - by using the stop button that controls the circuit breaker.

Step 6: Knowledge column
In Figure 36, aggregate knowledge demands can be derived from each functional entity in system representation. By collecting the demands, an operator knowledge profile can be compiled. Knowledge entities stretch across the whole system representation. For reasons of clarity, these are not explicitly drawn into the figures.

5.5 Summary of chapter 5

In chapter 5, the System Representation Matrix has been introduced, explained and exemplified. Ideas of how to use a developed system representation have also been shown. Further, a step-by-step procedure about how to use the System Representation Matrix to build a system representation has been suggested.

6 Evaluation of the System Representation Matrix

The evaluation of the System Representation Matrix starts with my own use of the method to analyse a batch process paint factory simulator. The evaluation continues with a session performed with three human factors engineering practitioners, where I acted as moderator of the analysis work. Finally, statements from two human factor professionals who have tried out the method in their technical consultancy work are provided.

6.1 Modelling example - the OPUS paint factory simulator

To exemplify and show how the matrix can be used to model a control room work system, a full scope paint factory batch process simulator is analysed. The batch process simulator was developed for the control room evaluation research project (project 6 in Figure 3) (Osvalder et al., 2013).

Figure 42. Paint factory simulator setup during experiments

To achieve an operator-working situation that was similar to a real world industrial control room, a paint factory simulator was built using the ABB 800xA control system. Thereby the Operational Performance and User Experience Laboratory (OPUS Lab) was created, including the OPUS Paint Factory.

For the experimental study for which the simulator was built, a paint factory was chosen on the basis of a generic batch process that is easy to understand and relate to, regardless of operator background (Osvalder et al., 2013). The choice of process was deliberately made with the intent of making it easy to interpret what is happening in the process, yet with the possibility of adding complexity by means of the number of objects present in the simulated environment, and by the amount of recipes that can run at the same time. The intention was that the paint factory should be quite easy to run during a normal operation that mainly includes operator supervision and inactivity, and which is often the case in process control in industry today.

In the experimental study, eight of the twelve test subjects considered the simulator to be realistic. The test subjects were operators with experience from various process industries (pulp&paper, food processing, water purification, heat & power, chemical processing, and oil refining). During the post-scenario debriefings, the operators gave their opinion of the simulator. Several of the operators considered the simulator to be very realistic (Osvalder et al., 2013).

The operator task when running the paint factory was to work with paint recipes. The following tasks were included in processing and control: input of batch recipes, start batches, monitor paint quality parameters, delivery of ready-made paint to storage tanks, cleaning of preparation tanks and refilling tanks with raw material. When mixing a batch a number of parameters were to be set, i.e. water content, various colour pigments (black, white, blue, green, yellow and red), thickening agents, binding agents and other additives.

Figure 43 shows an overview screen, with factory overview and a preparation tank with parameters to be monitored, as presented to operators when running the simulator. The paint production procedure and the simulated process dynamics were developed with input from subject matter experts from a paint factory in Gothenburg, Sweden. Four test subjects were used in pilot tests. First, two engineering students, who had performed their master thesis work on user interface design of process images, were included in functional tests of the simulator. Then, two process operators from industry participated to test the experimental procedure and the test tasks.

6.1.1 Paint production in the simulator

The first step of paint production in a paint factory simulator is to mix constituents (water, thickener and ammonia) in the preparation tanks (marked 200 in Figure 43). In the preparation tank it is possible to measure viscosity, temperature, pH, weight, volume and colour. The measured values are presented in relation to each tank. The input of recipes is made using the batch faceplate of each preparation tank respectively. After each recipe constituent has been added to the preparation tank the agitator is started. The agitation of the paint is controlled from the faceplate.

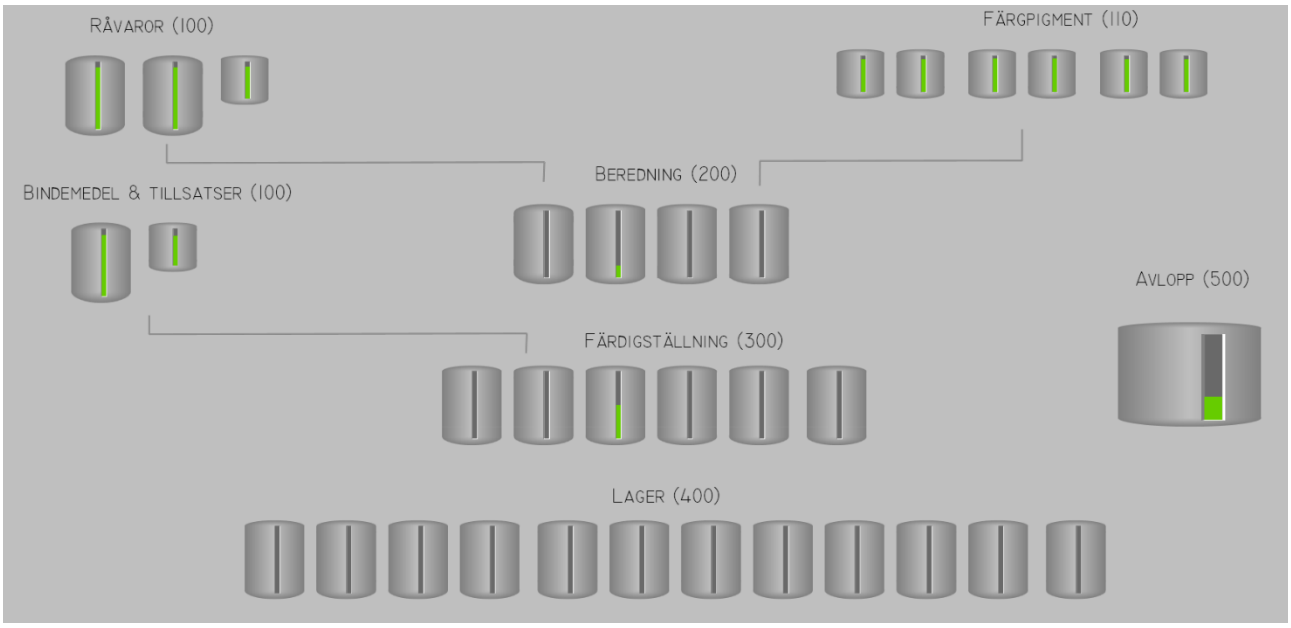


Figure 43. Overview display of tanks in the OPUS paint factory

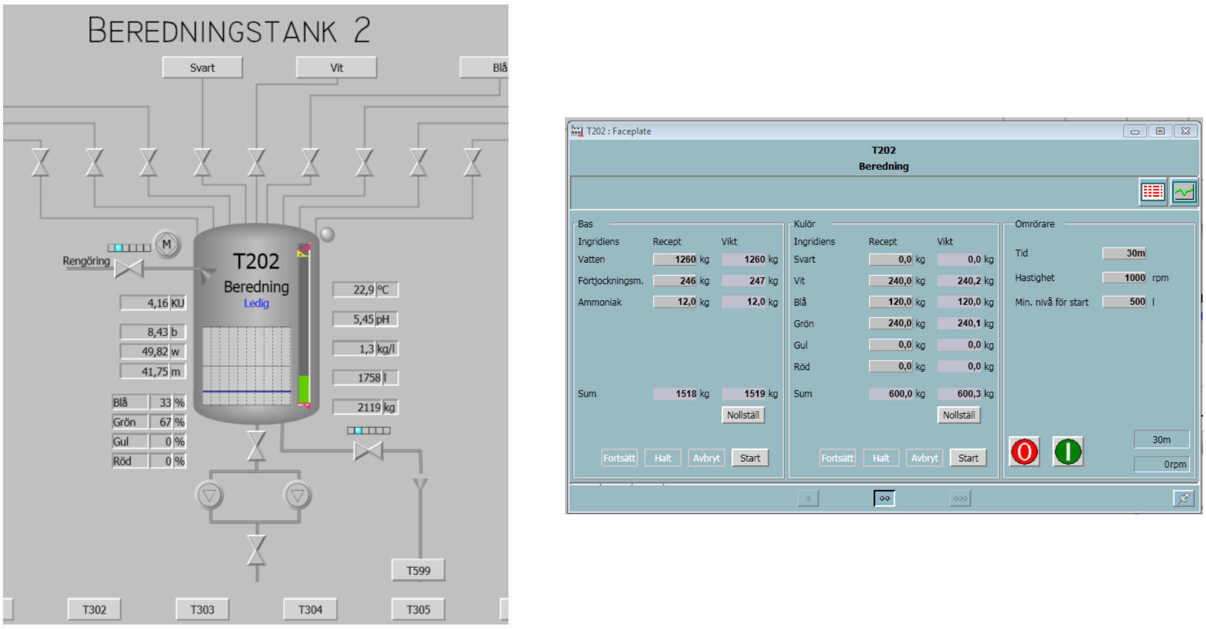


Figure 44. Preparation tank and the associated faceplate

The second step in paint production takes place in the completion tanks (marked 300 in Figure 43). In this step, binder and additives are first mixed, and then the liquid from the preparation tank is added, followed by additional mixing to ready-made paint. The completion tank is controlled from a similar faceplate as used for the preparation tank.

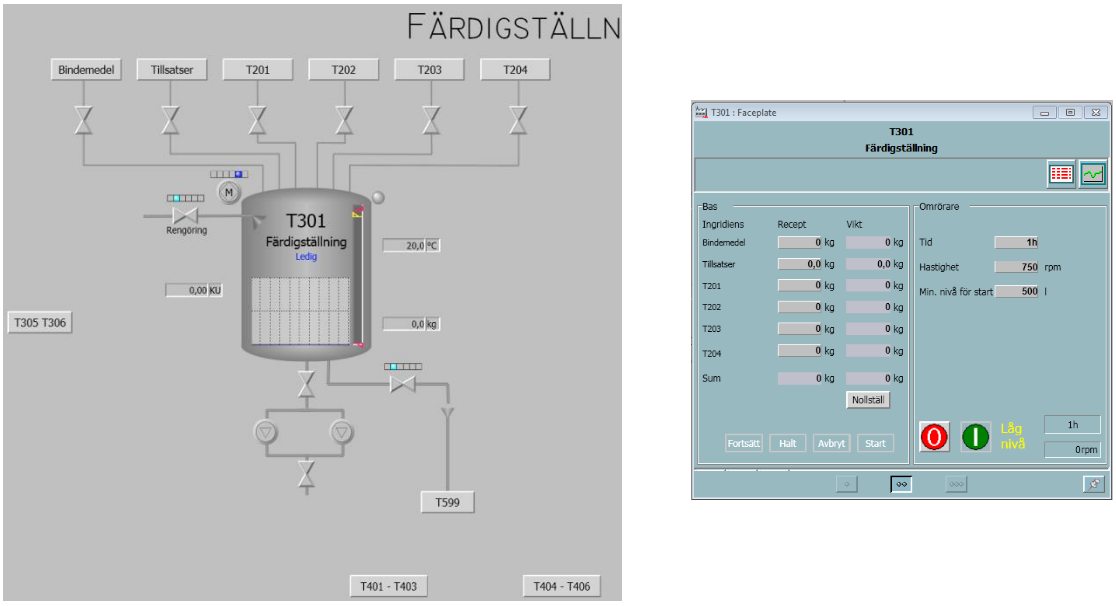


Figure 45. Completion tank and the associated faceplate

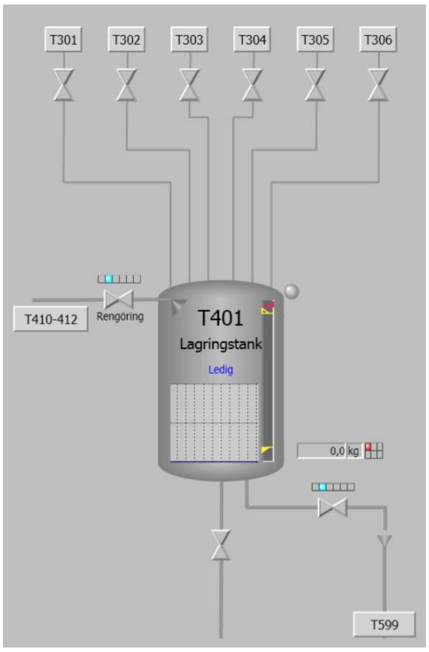
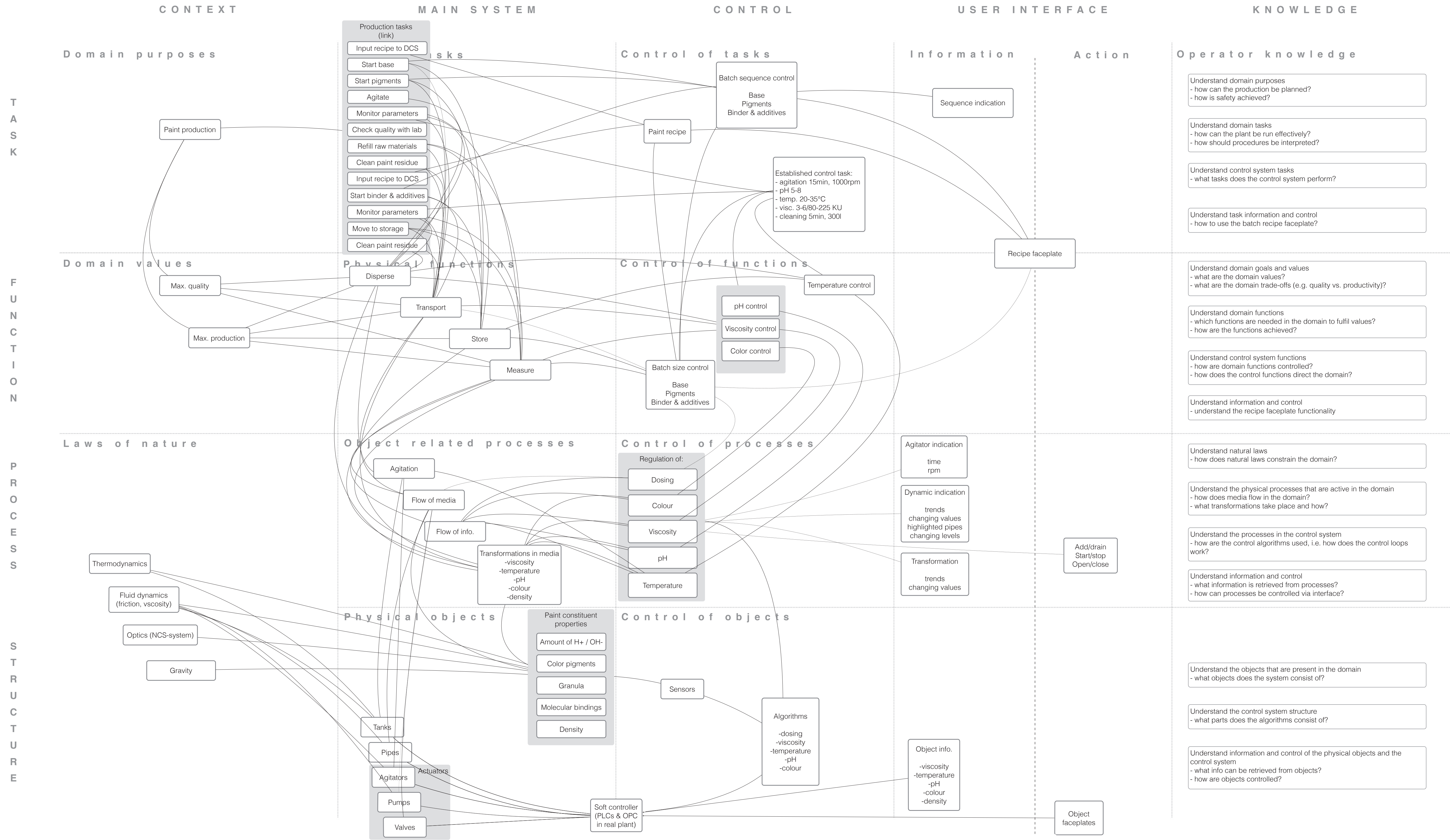


Figure 46. Storage tank

Finally the storage tanks (marked 400 in Figure 43) are filled. After this, the paint is transported to packaging and delivered to the customer.

6.1.2 The paint factory described using the System Representation Matrix

In this section the system representation matrix is used in the paint factory simulator. A system representation has been created by using the procedure presented in chapter 1. But each relation has not been defined in Figure 48-Figure 52, instead each relation of relevance is explicated in section 6.1.3, where examples of automation related challenges experienced in the simulator experiment (Osvalder et al., 2013) are represented using the method developed.


CONTEXT
MAIN SYSTEM
CONTROL
USER INTERFACE
KNOWLEDGE
TASK
FUNCTION
PROCESS
STRUCTURE
Domain purposes
Paint production
Production tasks (link)
Input recipe to DCS
Start base
Start pigments
Agitate
Monitor parameters
Check quality with lab
Refill raw materials
Clean paint residue
Input recipe to DCS
Start binder & additives
Monitor parameters
Move to storage
Clean paint residue
Control of tasks
Batch sequence control
Base
Pigments
Binder & additives
Paint recipe
Established control task:
- agitation 15min, 1000rpm
- pH 5-8
- temp. 20-35°C
- visc. 3-6/80-225 KU
- cleaning 5min, 300l
Information
Sequence indication
Action
Recipe faceplate
Operator knowledge
Understand domain purposes
- how can the production be planned?
- how is safety achieved?
Understand domain tasks
- how can the plant be run effectively?
- how should procedures be interpreted?
Understand control system tasks
- what tasks does the control system perform?
Understand task information and control
- how to use the batch recipe faceplate?
Domain values
Max. quality
Max. production
Physical functions
Disperse
Transport
Store
Measure
Control of functions
Temperature control
pH control
Viscosity control
Color control
Batch size control
Base
Pigments
Binder & additives
Understand domain goals and values
- what are the domain values?
- what are the domain trade-offs (e.g. quality vs. productivity)?
Understand domain functions
- which functions are needed in the domain to fulfil values?
- how are the functions achieved?
Understand control system functions
- how are domain functions controlled?
- how does the control functions direct the domain?
Understand information and control
- understand the recipe faceplate functionality
Laws of nature
Thermodynamics
Fluid dynamics (friction, vscosity)
Optics (NCS-system)
Gravity
Object related processes
Agitation
Flow of media
Flow of info.
Transformations in media
-viscosity
-temperature
-pH
-colour
-density
Control of processes
Regulation of:
Dosing
Colour
Viscosity
pH
Temperature
Agitator indication
time
rpm
Dynamic indication
trends
changing values
highlighted pipes
changing levels
Transformation
trends
changing values
Add/drain
Start/stop
Open/close
Understand natural laws
- how does natural laws constrain the domain?
Understand the physical processes that are active in the domain
- how does media flow in the domain?
- what transformations take place and how?
Understand the processes in the control system
- how are the control algorithms used, i.e. how does the control loops work?
Understand information and control
- what information is retrieved from processes?
- how can processes be controlled via interface?
Physical objects
Paint constituent properties
Amount of H+ / OH-
Color pigments
Granula
Molecular bindings
Density
Tanks
Pipes
Actuators
Agitators
Pumps
Valves
Control of objects
Sensors
Algorithms
-dosing
-viscosity
-temperature
-pH
-colour
Soft controller (PLCs & OPC in real plant)
Object info.
-viscosity
-temperature
-pH
-colour
-density
Object faceplates
Understand the objects that are present in the domain
- what objects does the system consist of?
Understand the control system structure
- what parts does the algorithms consist of?
Understand information and control of the physical objects and the control system
- what info can be retrieved from objects?
- how are objects controlled?

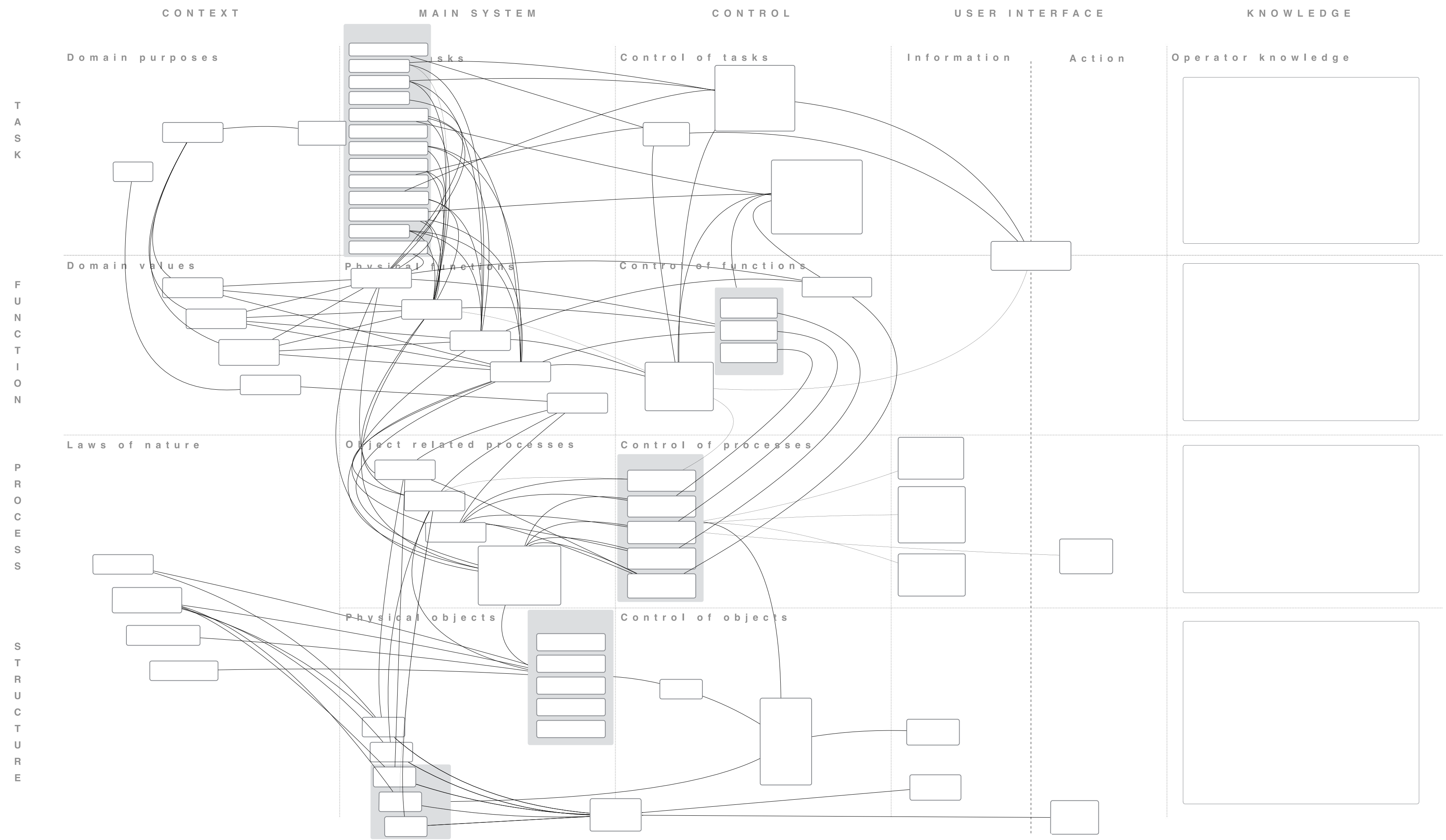


Figure 47. The Paint factory system representation (boxes are intentionally blank)

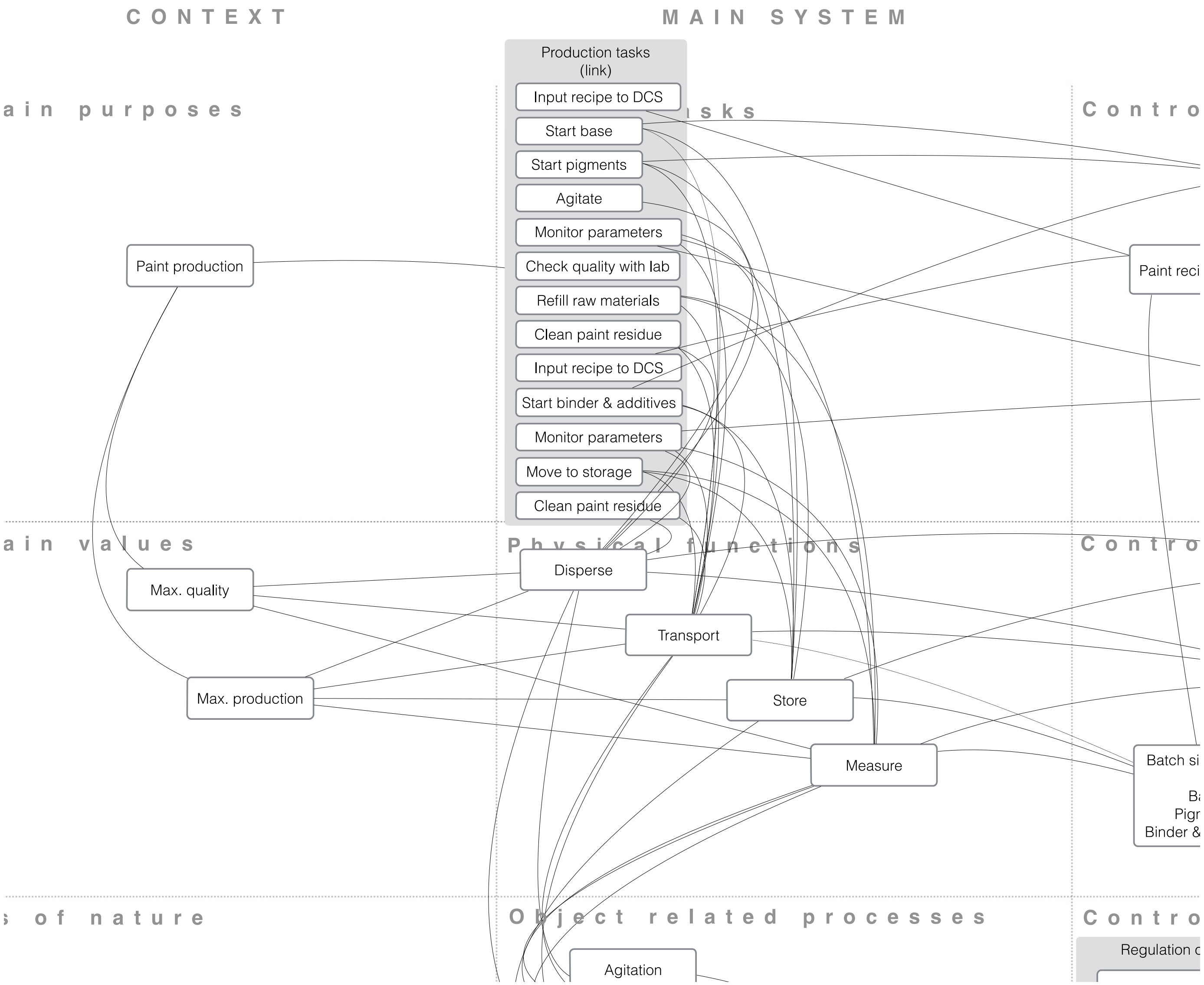


Figure 48. Upper left quadrant of the paint factory system representation

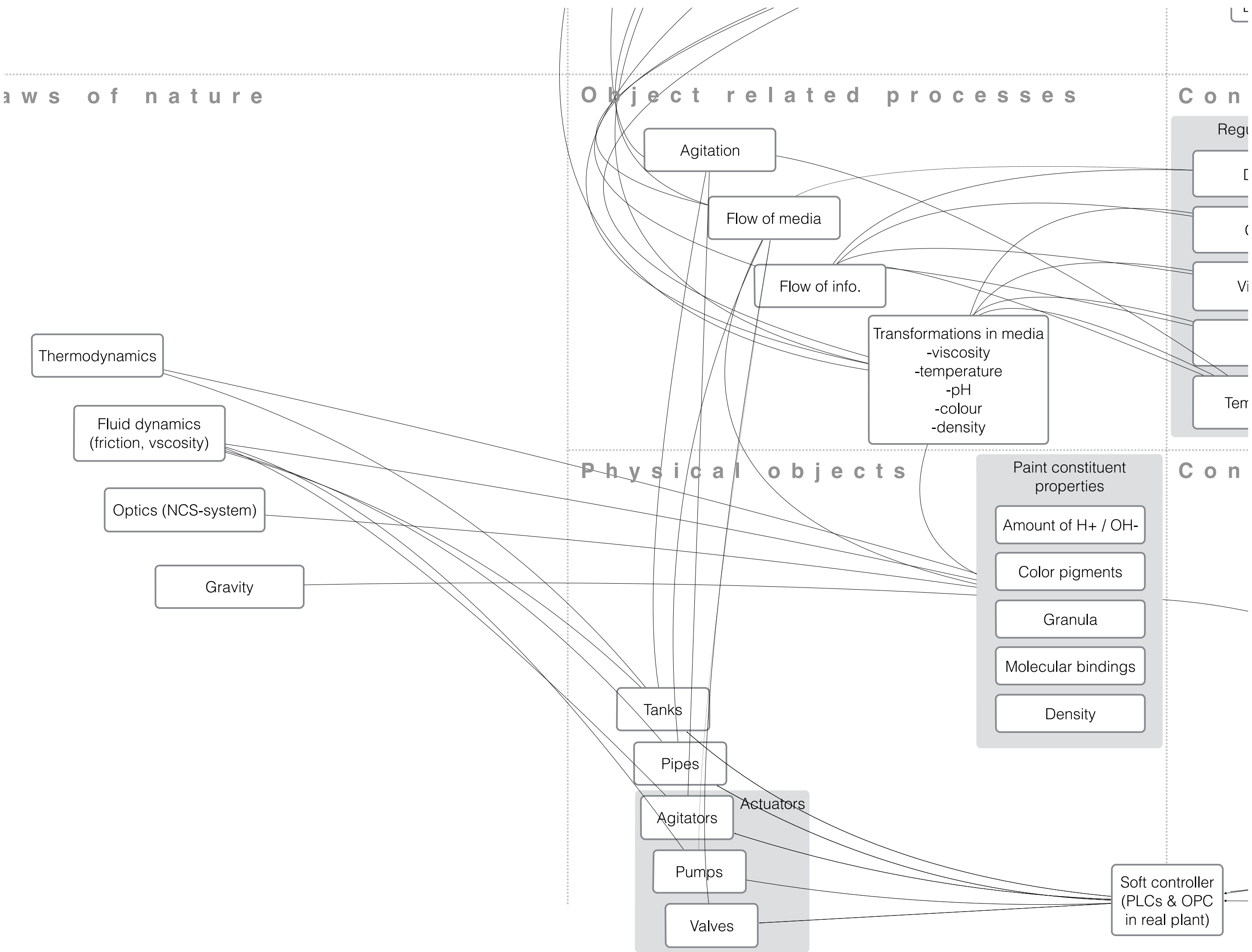


Figure 49. Lower left quadrant of the paint factory system representation

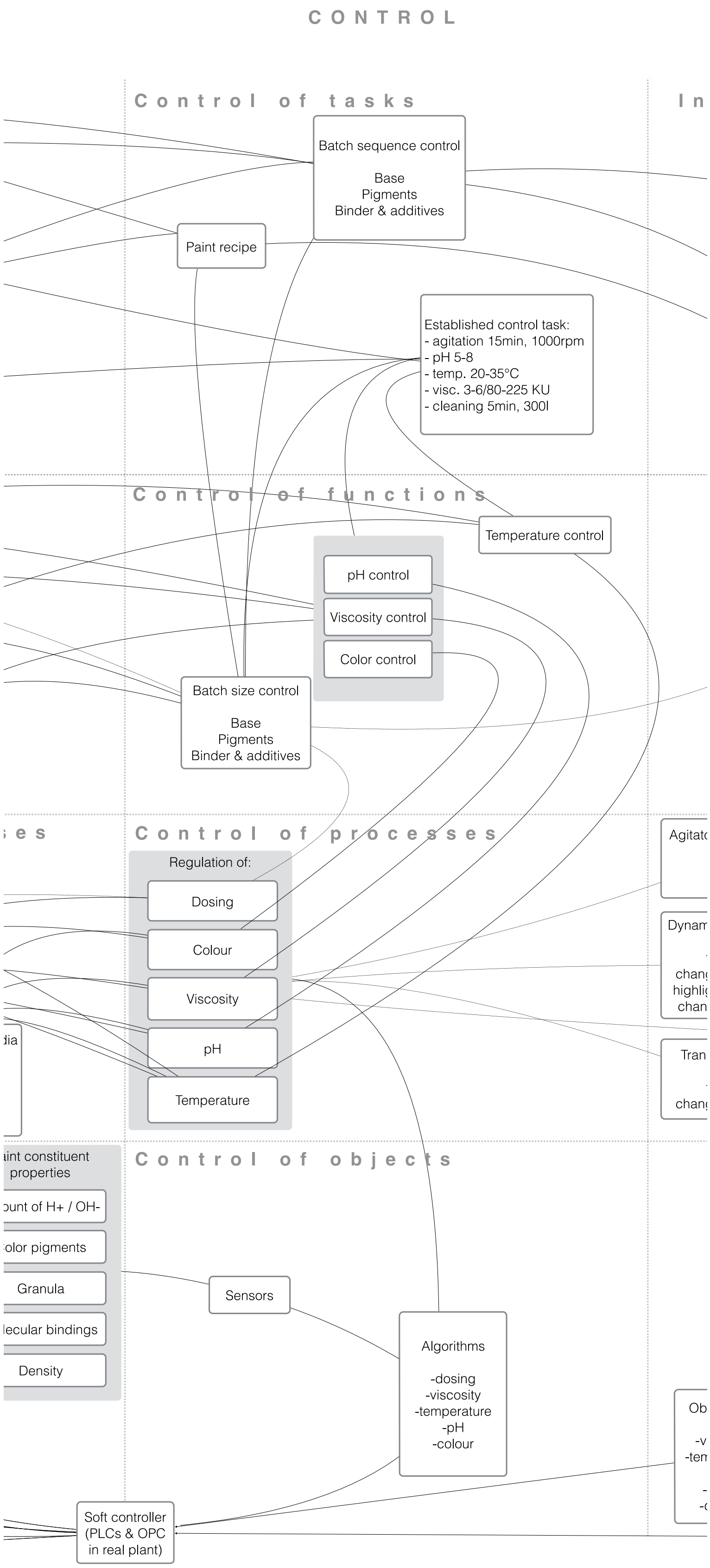


Figure 50. Control column of the paint factory system representation

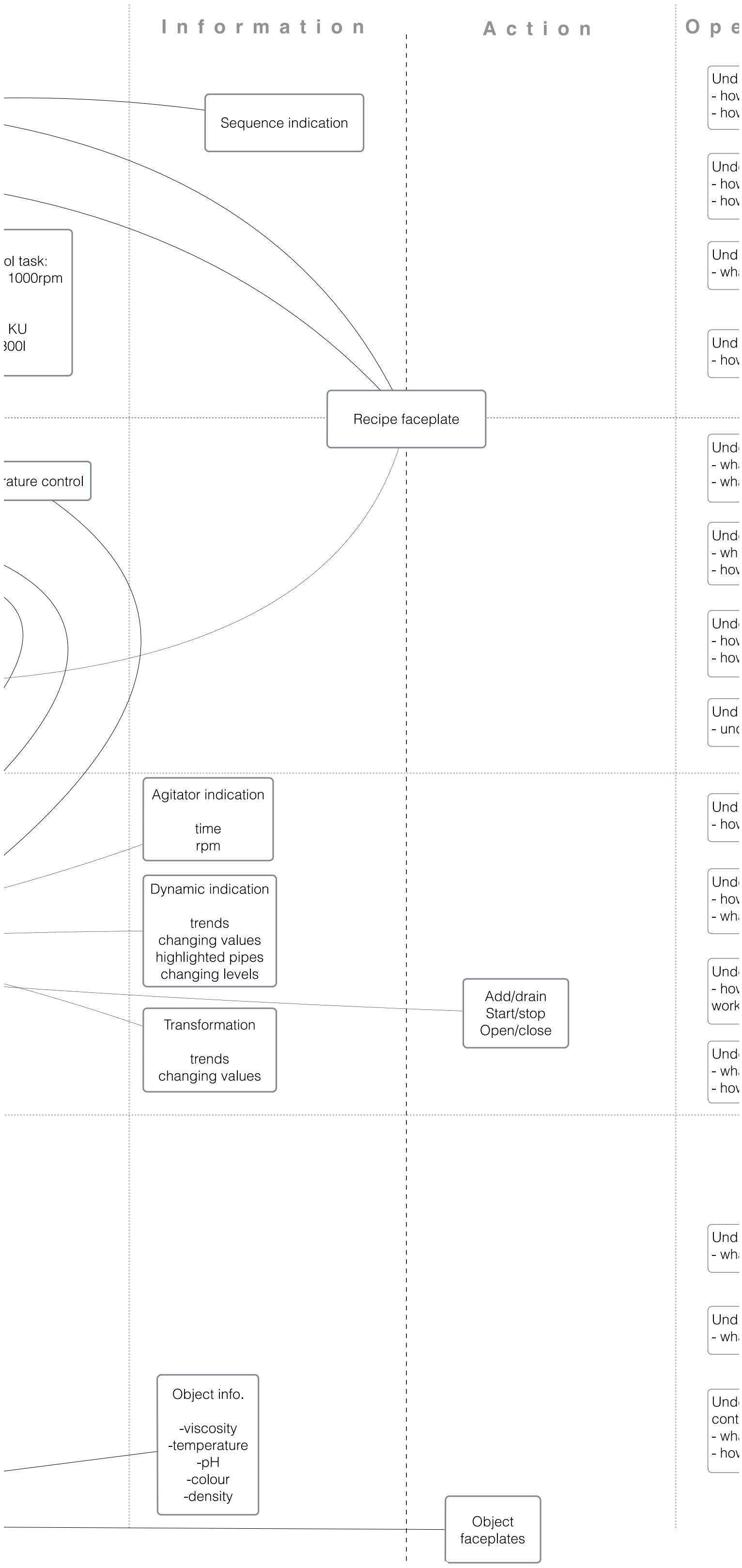


Figure 51. Control system user interface column of the paint factory system representation

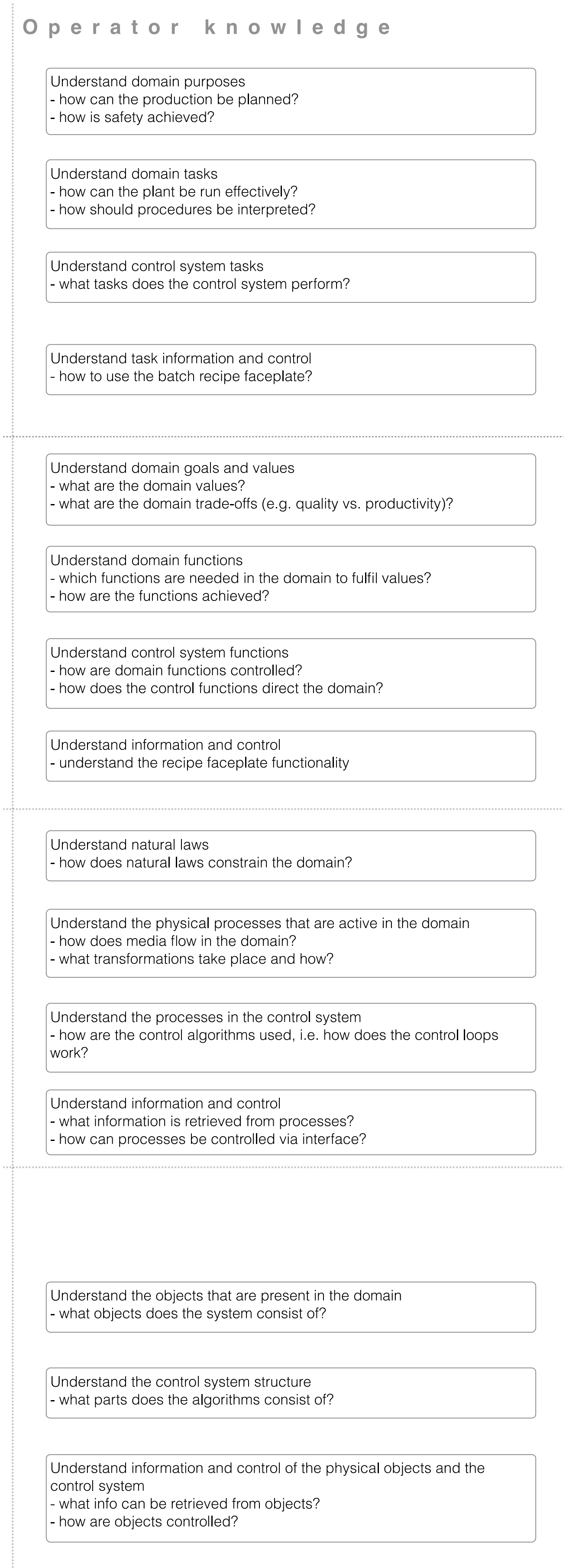


Figure 52. Knowledge column of the paint factory system representation

6.1.3 Using the simulator to represent automation related challenges

The purpose of this section is to connect back to the challenges described in section 2.6 and show how the developed System Representation Matrix can be used to pinpoint automation related challenges. The idea of the model presented in chapter 1 is that automation related challenges emerge as an effect of how the parts in a joint system represent each other. So, how can the relations and the resulting gaps be identified and represented in the System Representation Matrix when using the paint factory simulator?

During the simulator experiments (Osvalder et al., 2013) performed with the paint factory simulation, two automation related challenges were identified: brittleness and out-of-the-loop (I). These two problems have been described using the system representation matrix to assess how human-automation related challenges can be described and analysed with the System Representation Matrix.

Brittleness in the paint factory

In the control room experiments performed in project 6 (see Table 3), leaks were introduced in one of the failure scenarios. A leak in a tank that receives material during a batch sequence could potentially lead to a brittle failure if the control system tries to compensate for the lost material by filling up with additional material. Since the dosing control loop reacts on correct weight in the receiving tank, rather than on the material that has been drained from the raw material tank, a brittle failure scenario could occur.

Figure 54 shows an example based on the brittle failure scenario experienced during the paint factory simulator sessions. Next, the system representation is explained step-by-step.

1. Sensors measure weight in the receiving tanks, e.g. a preparation tank. The sensor gives input to the dosing control loop.
2. The dosing algorithm can calculate the deviation from the batch recipe based on the weight in the receiving tank. When the deviation is zero, the material flow is stopped.

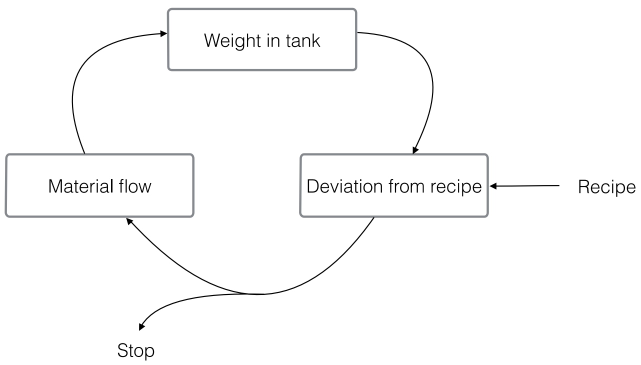


Figure 53. Dosing control loop

3. The dosing algorithm keeps the dosing process running until the weight deviation is zero.
4. The dosing process controls the flow of media (raw material, in this case). The flow will continue until the dosing process is stopped.
5. The flow of media fills the receiving tank with paint constituents. At the same time the raw material tank provides flow of media to the receiving tank.

6. The flow of media is dependent on the transport and store functions. The flow to the receiving tank will continue until one or both of these functions are not working, i.e. until the raw material tank is empty or until the leak is so big that no material reaches the receiving tank. It is probably here the brittleness will be revealed, if suddenly a function is lost. When a function is lost, the system will “crack” and the failure will be more easily revealed as a result of rapidly degrading system performance.
7. The transport, store and measure functions enable the control of batch size. The batch size control function directs the physical functions. If one of the physical functions is lost, batch size control is compromised. The batch size control function also enables the dosing process.
8. The batch size control function is represented in the interface by means of the recipe faceplate. The operator can enter recipe data and also monitor how much material is measured in the batch sequence. In the recipe faceplate the operator can see if a part of a batch is not complete by comparing digital values. The operator can also follow the dosing process by looking at level indicators and dynamic process values and trends, etc.

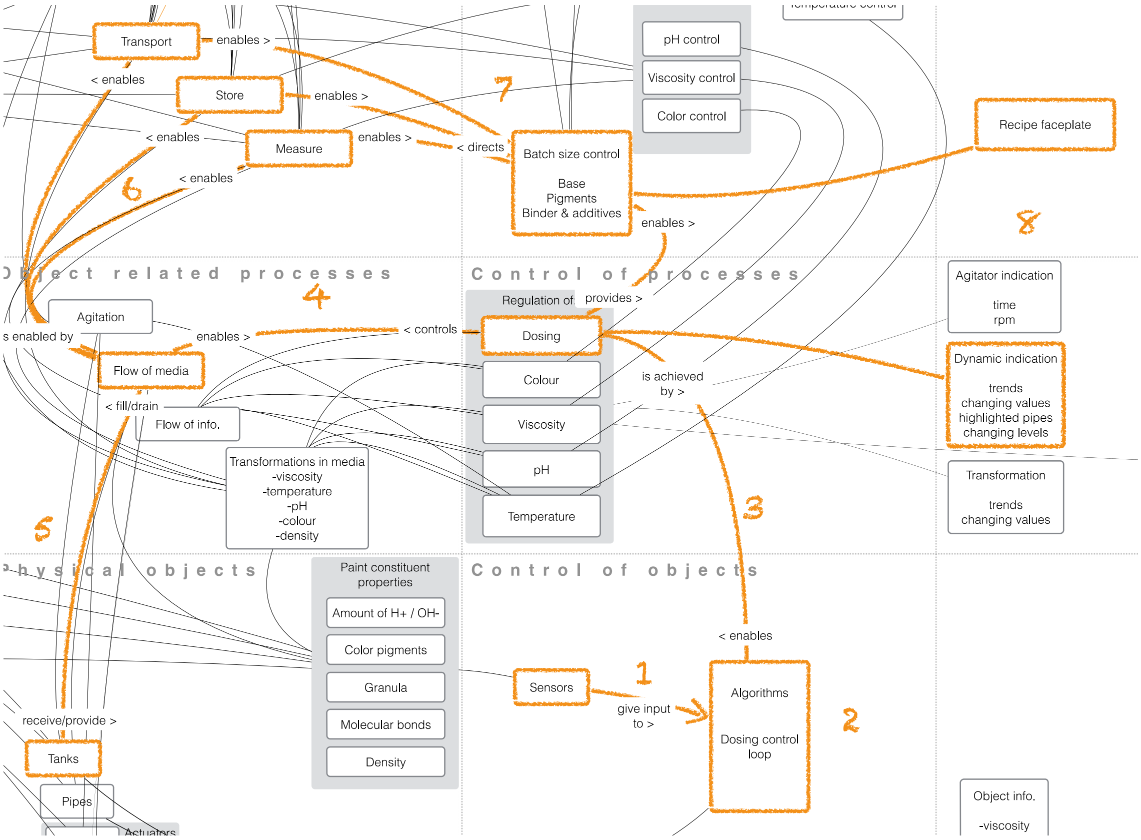


Figure 54. Brittle failure in the paint factory system representation

Representational gaps in the brittle failure scenario

Based on the system narrative illustrated in Figure 54 some conclusions can be drawn regarding the knowledge demands imposed on the operator in this situation.

Imposed knowledge demands

First we can conclude that there are entities involved from both the structure, process and function levels. The entities are interconnected by physical-, control- and information relationships. The system representation suggests that there is a need to have knowledge about the active entities and relations to understand the situation we just described. In general, the understanding is needed on how the dosing control loops work to enable dosing and how batch size control is achieved. To detect a brittle failure the operator needs to acquire knowledge if there is a place in the plant where the sum of flows does not add up correctly. With 11 raw material tanks and 21 possible receiving tanks in the paint factory a manual monitoring task can quickly become challenging.

Operator support
In the control room the operator has access to information from the control system interface. As indicated in Figure 54, the main sources of information in this situation are the recipe faceplate and dynamic indications related to the dosing process. The information makes it possible to see that, e.g. a batch is running, and that material is flowing from one tank to another. This kind of information is mainly related to the process level, i.e. that something is going on. There is also information related to how the batch size control function is achieved, i.e. the recipe faceplate shows the steps of the batch sequence and tanks that are involved to achieve the batch. The operator also has access to recipes and procedures, not to mention field operators that can perform checks outside of the control room (collaboration with field operators were also a part of the simulator experiments).

Gap between demands and support
To detect the failure the operator has to continuously know that the difference between the inflow and outflow between different locations in the paint factory is zero. The lack of integration of information to support this notion creates a potential gap between the main+control system and the operator. Reducing the gap would require extended measurement of flows in the paint factory together with improved integration of information.

Out-of-the-loop (I) in the paint factory
In the control room experiments performed in project 6 (see Table 3); the operators perceived the fluctuations in viscosity as difficult to understand since the viscosity parameters fluctuated in unexpected ways. The viscosity of a mixed fluid (e.g. paint) is determined by the combined viscosity of the constituents and the temperature of the fluid (increased temperature results in lower viscosity). The combined viscosity of several fluids is however not linear to the viscosity of each of the constituents. The combination of up to nine different paint constituents and changing temperature due to agitation makes the viscosity parameter challenging to understand and predict in the paint production simulator. The viscosity is controlled by either adding binder (to thicken) or water (to dilute) until the viscosity is within the allowed range (see the viscosity control loop in Figure 55). In this case, the operators' difficulty of understanding how viscosity fluctuates can be categorised as an out-of-the-loop problem since the information in the control system interface does not reveal what is happening. In this particular example it originates from the transformations in the mixed paint being complex, and the means for following what the control system is doing.

Figure 56 shows an example based on the out-of-the-loop situations experienced during the paint factory simulator sessions. The system representation in Figure 56 is explained in three steps.

1. Viscosity changes dynamically as different raw materials are added, resulting in transformations in the paint. The main difficulty in this situation lies in understanding how transformations take place when different paint constituents are mixed. The

transformations of viscosity are defined by fluid dynamics and caused by molecular bonds between constituents.

2. The viscosity control loop (Figure 55) receives viscosity measurements from sensors in the preparation and completion tanks. If the viscosity measurement deviates from what has been specified in the paint recipe, the viscosity is adjusted by adding binder to thicken, or water to dilute the paint.

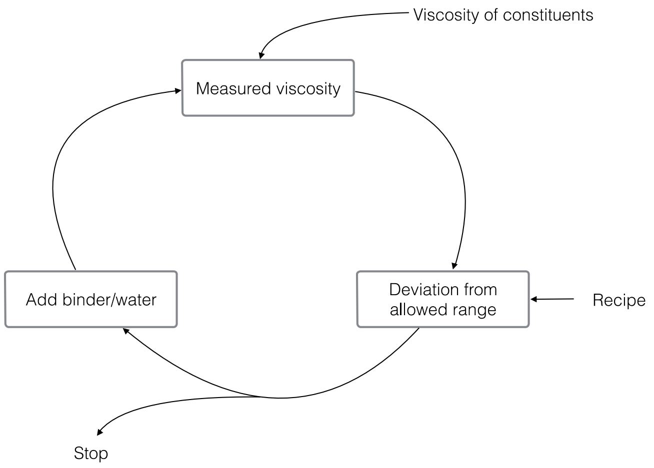


Figure 55. Viscosity control loop

3. In the paint factory simulator, the transformation in the paint is indicated by changing values from the measurements associated with each tank. The values can also be displayed as trend diagrams. There is however no display that support understanding of how the viscosity can be expected to change, i.e. support for how viscosity can be controlled.

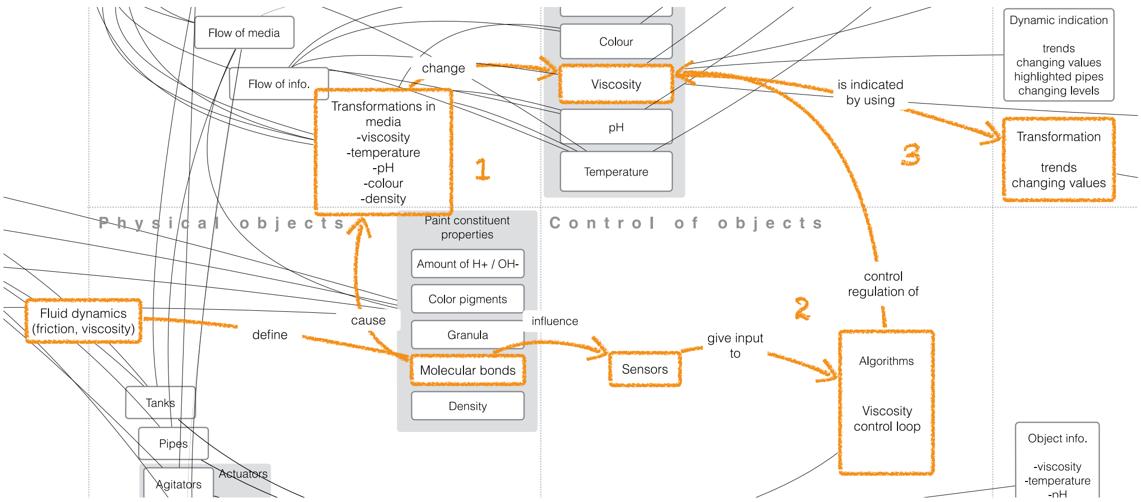


Figure 56. Out-of-the-loop (I) in the paint factory system representation

Representational gaps in the out-of-the-loop scenario

Based on the system narrative illustrated in Figure 56 some conclusions can be drawn regarding the knowledge demands imposed on the operator in this situation.

Imposed knowledge demands
In this situation entities and relations on the structure- and process levels are involved. The system narrative points out that there is a need for knowledge regarding fluid dynamics, paint constituent properties and the transformations in the paint to understand why viscosity changes during mixing. Knowledge is also needed about how the algorithms work to understand how viscosity is controlled.

Operator support
Information regarding viscosity is obtained from the viscosity measurements associated with each tank. Trends curves of the digital values can also be viewed.

Gap between demands and support
The most apparent gap between the knowledge demands and the existing operator support is that lack of information on how the viscosity can be expected to change during mixing of several constituents. Reducing this gap would require a model (analytical or empirical) of the non-linear fluid dynamics that can aid the operator with what to expect in terms of changing viscosity when mixing paint constituents. The easiest way to reduce the gap is not necessarily to display more information; it can also be reduced in terms of educating the operator in fluid dynamics.

6.1.4 The System Representation Matrix in multidisciplinary work – an example

The out-of-the-loop problem also offers an opportunity to explain how multidisciplinary work benefits the analysis of automation related challenges mapped as a system narrative onto the model of the paint factory. It starts with an operator who expresses a problem with understanding why the viscosity measurement changes the way it does during mixing. The idea of this example of the out-of-the-loop problem comes from the simulator experiments performed in project 6 (see Table 3).

The following hypothetical dialogue takes place between the operator, the process engineer, the control engineer and the interface designer, in an effort to improve the understanding of the behaviour of paint viscosity.

Query posed by operator:
"The measure of viscosity changes during mixing in unpredictable ways and is difficult to understand. I suggest we try to improve control and the interface so the operators can obtain a better understanding of the viscosity parameter."
(An instance of the out-of-the-loop problem)

Response by process engineer:
"Well, we have sensor equipment to measure this sufficiently well to ensure high quality in the end product. But we don't have any good process models to calculate it beforehand. We don't really know what happens in terms of molecular bindings when we mix our batches."

Response by automation engineer:
"The viscosity changes with temperature, but that fact is not included in the control loop. Maybe we could somehow include the impact of temperature."

Response by interface designer:

”Ok, I will look into how we can use graphic builder tools to reflect the process better. I will change the single measured value to a trend to begin with. Then I will think about how we can visualise the interdependencies, so the operator can predict the final viscosity more accurately.”

In Figure 57 the system narrative is displayed in the paint factory system representation. The different designer roles have been marked with separate colours, which correspond to the model in chapter 1.

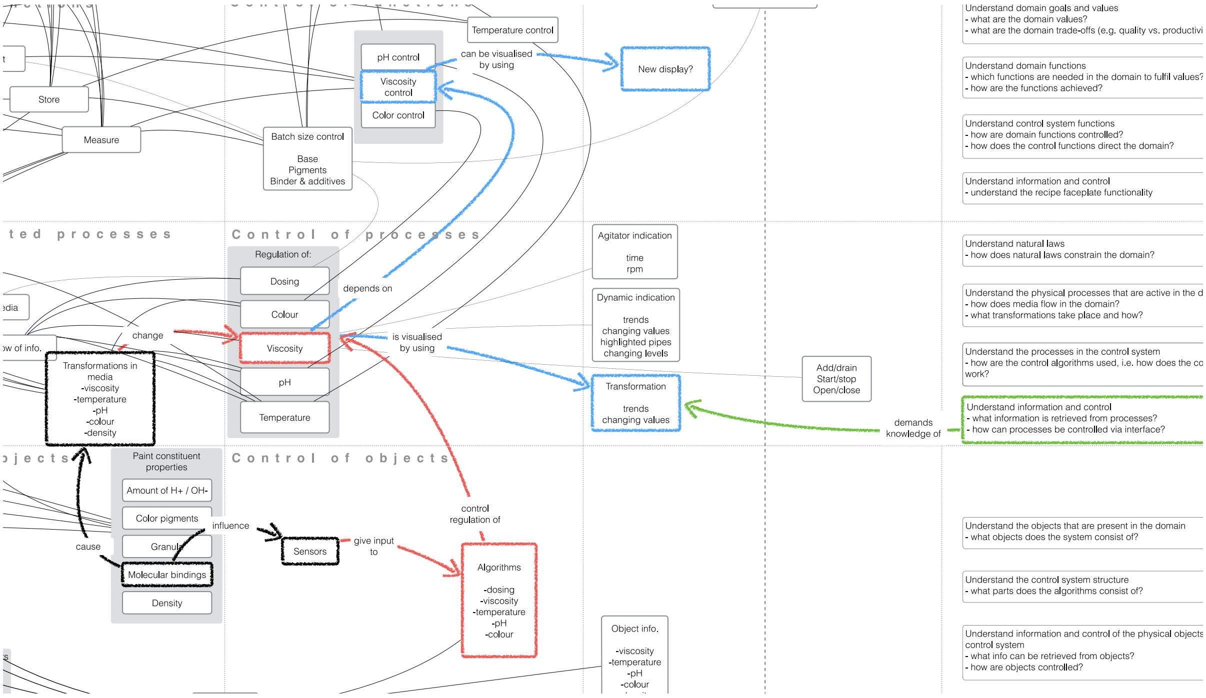


Figure 57. Out-of-the-loop discussion between the operator (green), the process engineer (black), the automation engineer (red), and the interface designer (blue)

6.2 Test session with human factors engineering practitioners

Empirical evaluation with human factors engineering practitioners is presented in two steps. First, the method evaluation procedure is described. Then the participants' opinions and reflections are presented.

The purpose of the empirical evaluation was to test the method with human factors engineering experts, and to discuss the practicalities of the method. The evaluation was made based on three perspectives:

- Can the method be used to make system descriptions?
- Can the method support design?
- Practical use - is the method adapted for industrial practice?

The aim of the evaluation session is to obtain an overview of the method's strengths and weaknesses, based on the experts' opinions.

Participants

Participants were three human factors engineering practitioners with 9 to 15 years of experience from working with research and as consultants in industrial domains. All participants were experienced users of human factors methods, and all had experience from research in academia; one with a licentiate and one with a PhD degree. From their knowledge, practical experience and education level they could all be considered experts in the field of human factors engineering.

Evaluation procedure

One week before the evaluation session, a method description (similar to the description and example given in section 5.1-5.4. The detailed procedure in section 5.4.1 was, however, not yet developed at that time) was sent out to the participants to read before the meeting. At the time of the evaluation session, the evaluation moderator (the author) first presented the purpose of the evaluation to the participating HFE practitioners. Then, the method description was reviewed and clarified and questions were answered. After that, the case chosen for the evaluation was presented – adaptive cruise control of a car. The adaptive cruise control system was presented by screening a 2 minute commercial from Ford. The film briefly showed how their adaptive cruise control worked and how it was operated. The participants were given a one page description of adaptive cruise control on paper. After viewing the film and reading the paper, the system was discussed and some questions regarding the system were clarified to provide participants with the same conclusions as to how the system worked.

The adaptive cruise control system was chosen, since it was considered a human-machine system well defined in terms of system boundaries. Further, adaptive cruise control is a system that includes automation, which is of interest to evaluate using the method. It was also chosen, since all method participants were judged to have a fairly similar knowledge level of cars. This was the main reason for not choosing for example, a subsystem in a process industry, where participant knowledge level would have been too disparate. An analysis of adaptive cruise control was also judged as achievable in terms of completing an analysis within the time limit of the session (4 hours).

The introduction took approximately one hour, then the participants performed the method for two hours, and one hour was used to discuss and evaluate the method from three perspectives: ability to represent a system, ability to give input to design and the method's applicability in the practitioners' work in industry.

To kick-start the evaluation, participants were recommended to start with identifying entities on the Structure level and writing them on post-its. The matrix was drawn on a whiteboard and levels were marked 1-4 and the columns A-E and the post-its were placed in each corresponding cell. After that, an attempt to draw all relations was made. However, this was complicated by the extent of entities identified in combination with the size of the whiteboard. Instead, participants focused on building a system narrative based on questions set by the session moderator, thus focusing on a subset of entities involved in each question.

6.2.1 Results from empirical evaluation

The evaluation session was completed with a discussion of positive and negative aspects of the method from three perspectives: the method's capability of aiding system description, the method's perceived ability to support design, and how easy or difficult the participants thought the method was to use.

Can the method be used to make system descriptions?

According to the participants, the system representation facilitates a holistic understanding of the system and seeing the relation between parts and whole of a work system. The participants found it easy to get lost in complexity – the analysis has to be clearly delimited to be possible to perform in practice. The web of entities and relations has to be possible to handle in practice for the analysis to be useful. There is a balance between wanting to describe reality with its real complexity, and at the same time having to stay on top of the analysis without getting bogged down by too many details.

One way the participants found to keep the balance between overview and detail, was the importance of clearly stating the purpose of the analysis in advance. A clear purpose will help delimiting and focusing the analysis on relevant parts. At the same time, this contradicts the usefulness of achieving a holistic view of a system. Clearly, complexity cannot be escaped, but has to be balanced in relation to the question at hand.

The participants found that the description of what each cell in the matrix should contain had to be defined more concisely to facilitate understanding. Some cells were found difficult to describe. In general, the identification of entities was straightforward, while drawing the relations was more difficult. However, the drawing of relations was found to be useful, and missing entities could be specified as "holes" in the system representation.

One of the major strengths according to the HFE practitioners was that the method provides an overview of the system, including for matters not specifically driven by the human factors engineering agenda, i.e. automation or process design issues.

Based on the evaluation and the comments from the participating human factors engineering practitioners it can be concluded that it is possible to use the System Representation Matrix to describe a human- machine system.

Can the method support design?

An important part of supporting design activities is to aid specification of design requirements. After using the method, participants stated that the system representation matrix had the potential to offer a systematic approach to requirements specification by relating requirements to each entity included in the system representation. If you ask the right questions of the system representation, you will obtain a basis for design requirements. However, as one of the participants concluded, the challenge is to pose the right questions.

According to the participants, demands in projects often come from different parties and activities, and the method can here be used to map existing needs and demands onto the system representation, using it as a holistic overview. Participants were not certain that traceability could be achieved by means of the method, however the system representation could be used to unify and map different analyses and design activities.

Participants also stated that the method can be used to motivate design decisions. The method can be used to point out where something is missing and needs to be complemented to fulfil a functional need. This approach presupposes a sufficiently adequate system representation, which imposes a need to validate the representation.

Another perceived benefit of the system representation was that requirements for education and training arise naturally during analysis and these needs were perceived to be expressed more easily than design requirements.

However, participants also pointed out that not all aspects of design work are supported. For example, practitioners commented on the method in its present form giving little support as to how to realise the actual design. They also said that, by specifying the functions that are necessary to fulfil the system purpose, the method can nevertheless aid functional specification. There is, however, no specific aid provided as to how functions should be realised in terms of physical objects and processes. When used to analyse existing human-machine systems, the components and processes are already there to be explored and evaluated if new functions can be fulfilled with existing equipment. They concluded that, in new systems where physical solutions have not yet been realised, the functional analysis can aid identification of design requirements based on functional needs.

Practical use - is the method adapted for industrial practice?

Participants stated that the identification of entities was perceived as easy, but drawing relations and performing a relevant analysis requires the availability of in-depth system knowledge and human factors engineering competence in the development team. Questions were posed regarding how the method relates to existing methods, e.g. task description techniques (i.e. HTA) and human error analysis methods. The questions indicate a need to further explore how to integrate results from different established methods.

The participants pointed out the need to have a basic understanding regarding levels of abstraction and the means-ends hierarchy, and that users not used to this way of thinking might find the method difficult. The specific need further shows the importance for human factors engineering experts to be an integrated part of development teams.

The participants saw benefits of the system representation as a way of providing different perspectives to the disciplines in a development team. A single discipline cannot fill out the whole matrix effectively, which was also experienced by the participants (e.g. comments like "*now we need a control engineer with knowledge of the control algorithms*" were expressed by the participants), since the need for specific knowledge becomes explicit when the need for multidisciplinary work becomes apparent.

The question of whether the method will facilitate communication between disciplines was also posed. Participants agreed that it could be useful as a mediating object to facilitate communication between different disciplines in the design phase. One participant stated that for example, presenting a hierarchical task analysis to an engineering department might be met with confusion, while a system representation where functional and physical components are described might work better.

Comments on procedure

Participants also commented on the procedure of creating the system representation matrix. They found it difficult to know exactly what to describe in the different boxes, since they experienced that similar things could be written in several places. This indicates that the descriptions of how to categorise content in different cells in the matrix have to be clarified, and a categorisation of how to formulate entities at different levels of abstraction need to be defined.

For practical use in industrial projects participants suggested the construction of a system representation could be divided into several sessions. For example, one session could be used to create the upper left quadrant, and another session could take care of the control column, etc. Sessions could also alter between working in groups and then having one analyst refine system representation before iterating the procedure. The system representation can then be built and refined according to needs in different phases of the development process. The participants also expressed the importance of a skilled session moderator to guide the multidisciplinary team of analysts. Clear guidance is needed to attain good results and support acceptance of this kind of new approach.

To summarise the evaluation, it can be concluded the method can be used to create a system overview useful to support design decisions, but there is little support as to how a specific design solution should be realised.

6.3 Application in industry

Two human factors engineering practitioners working in technical consultancy were asked to use the method in their work. They were given the same introduction material as for the evaluation session, but the work was done individually with little support from me as a method designer.

Statement from human factors engineering practitioner 1

The first of the practitioners, who tried the method in industrial use, used it to build a system representation of a system for chlorination of feed water. The purpose of the analysis was to support design of a control system user interface and associated procedures. After having worked with the method for some time, the participant was asked to summarise experiences from using the method, which are briefly summarised below.

- The method is possible to perform in industry
- It is difficult to limit the analysis and know where to start
- The analysis can become very large
- Larger projects would generate enormous matrices and many relationships, both within the system and between systems
- The method became cluttered when I drew many tasks at once

- A scenario has to be chosen in order to obtain an overview
- Being able to start anywhere in the matrix is positive
- I started to think through scenarios, to make it easier to project my thoughts into the matrix

A possible improvement would be a computer aid that could be used to draw relations and highlight a specific scenario.

Comments on applicability in industry

- I believe that the model would be a good common platform for a multidisciplinary plant development team. It can help different disciplines to understand each other in a better way.
- It could also facilitate human factors engineering issues being understood better if everyone can obtain a holistic view and use that common view as a starting point.
- If it was possible to talk about the system on a general level and then move down to details and if it was possible to visualise this, then I believe human factors engineering will be easier to understand for non-practitioners. Customers/clients will also understand the concept of using a structured method. This would make my work understandable and visible to others. I believe this will benefit human factors in industry in general.

Statement from human factors engineering practitioner 2

The second practitioner chose to focus analysis on adaptive cruise control in cars, since this was the practitioner's area of expertise. Before starting analysis work, the purpose of the analysis was stated as to "Explore how well drivers can work with the adaptive cruise control in ordinary traffic conflict situations, e.g. when another car cuts in".

- When working with the matrix I experienced a need to describe the task from both system and the driver point of view. It is not certain that task of the automation overlaps entirely with the task/goal of the driver in this specific situation.
- Scope of the analysis permitting, it could be good to be able to include the aspects of operational, tactical and strategic thinking.
- In the control/structure cell, the limitations of sensors and algorithms were included. This made the representation more complete, since all systems have limitations.
- I found it important to keep focus on the initial scope to achieve an analysis, and not to digress to e.g. social aspects of driving, the choice to select eco driving etc. although this could impact how the driver chooses to use the system.

Building a narrative

- During the building of a narrative I noticed a way to account for effects in "reality" was lacking. It was difficult to remember to include things not directly related to the system, such as the "toast colour" example. This is because that aspect is not included in the *system's* image of the process working correctly. The technical system itself can tell if it considers the system goal to be achieved, and then display accordingly. However, this might not be correct (e.g. due to technical faults) and therefore something has to be included connected to the "real" reality, and not only the reality as perceived by the technology. This might be caused by using the word "interface" and its association with graphical user interfaces – the interface of reality is often forgotten.

Conclusions made by practitioner 2

- When using the matrix it was clear that knowledge demands imposed on the driver are not represented elsewhere in the matrix. These become more like something the human needs to do/think about, particularly when comparing system functioning and effects in reality.

- Effects in reality versus effects the interface show, is not something one spontaneously includes in the matrix. For example, if toasters had had sensors for toast colour, would this be enough, when considering the content of the method? At least there will be no empty cells in the matrix. How should demands imposed on humans to assure safe functioning, be made explicit? Should these also be imposed in situations control engineers fail to think of?

- There are sensors in the case of adaptive cruise control, but it is not certain they see what they should. In the toaster example, toast colour is not visible to the user even if they wanted it to be. But in the case of an adaptive cruise control, the distance to the car in front is visible to both driver and system (through interpretation by sensors+algorithms). Thus control is shared by both human and system. But it is up to the driver to decide if system action is appropriate in the current tactical situation.

6.4 Reflections from a fellow method developer

The following section presents some reflections from one of the researchers in the method development team. The purpose of including the reflections is to provide a view from all of the contexts where the System Representation Matrix has been used until now. : In my own explorations of how human-automation challenges can be explained, by practitioners in a moderated workshop, in industry without support except from an introduction on paper, and back again to the research team.

The bullet points reflect the words of a researcher in the development team.

- My main idea when working with the development of the System Representation Matrix has been to unite all aspects that are important in a human-machine system to show how the different aspects are related.
- Previously, I have tried using Work Domain Analysis, but I found that it has not worked all the way. The System Representation Matrix gave an opportunity to create a structure using the same basic idea as Work Domain Analysis but better adapted to my needs. One need was to show both the systems external constraints together with the regulation of a human-machine system.

- I believe that for the System Representation Matrix to become an acknowledged tool in industry there is a need to develop software that makes it easy to add and organize entities and relations. Also, it would be beneficial if you could visualize and save different relation patterns that are of interest.
- In the development of the System Representation Matrix I have applied the method on various artefacts such as spoon, thermostat, water tap, flatiron, coffee machine, and microwave oven, to explore how the model was working in relation to different

human-machine systems. The development has been made by repeatedly testing and modifying to achieve continuous improvement.

- The choice of the structure, process, function, and task levels came from earlier research work. Previously there was also a situation level, but it has been removed.
- Performing modeling in the left three columns (context, main system and control system) I consider working well. However I have not found the same coherence in the right part of the matrix (control system user interface and operator knowledge) as yet. It is rather unclear how the user interface should be linked to the regulation and how the operator knowledge can be better integrated with the other parts.
- An idea for further development of the System Representation Matrix is to split the operator knowledge column into two parts. One part can focus on operator knowledge and the other part can then focus on the decision making.
- I believe that the System Representation Matrix suffers a lot from being presented in only two dimensions. It could be made much clearer in 3D if the columns were shown as domino tiles so that the operator knowledge can be placed behind all of the columns to easier show a projection of knowledge needs related to each column

- The main benefit of the developed System Representation Matrix is the way it combines and unites many different aspects in a human-machine system. From physical laws to human cognition. The matrix can be used to show how these aspects are related in a unified representation.
- The main difficulty with the System Representation Matrix is to determine which level of detail an analysis should be performed in. The descriptions easily become complicated and you get bogged down by too much detail.

To conclude, it seems like the developed method is possible to use in a wide range of applications but that the means for handling complexity and level of detail in an analysis has to be improved. It is considered a strength that the System Representation Matrix can combine several perspectives of human-machine systems and integrate them into a unified view.

6.5 Summary of chapter 6

Results from four evaluations of the System Representation Matrix have been presented. The examples show three types of use: method use by the method developers, use by human factors engineering practitioners moderated by the method developers, and use by human factors engineering practitioners independent of the method developers. The evaluations reflect the effort to make the System Representation Matrix into a method both useful and usable to other human factors engineering practitioners.

Based on the findings in the three use scenarios, conclusions have been drawn regarding the fulfilment of the method requirements developed in chapter 4. These conclusions are presented in the next chapter.

7 Fulfilment of method requirements

Chapter 7 is a discussion of how each of the forty-six requirements to achieve a useful and viable method developed in Chapter 4 has been fulfilled. Each need is briefly reviewed and followed by a ranking (High (H), Low (L), None (N)) of how well each need is considered to have been met.

Requirements	Is the requirement fulfilled by the System Representation Matrix? Level of fulfilment: High (H), Low (L), None (N)	
GENERIC REQUIREMENTS (from Table 7)		
- help the designer deal with complexity by enabling fluent shifts between levels of detail and abstraction	The levels of abstraction enable description of multiple levels of analysis. The level of detail has to be chosen with respect to the purpose of the analysis. There is no specific guide on how to define the boundaries of the system representation.	L
- have a unified format to describe dynamic domain, control system, control system user interface and operator knowledge.	The same format, i.e. entities, relations and system narrative are used across system parts.	H
- help define interconnections and dependencies by explicitly representing relations between dynamic domain and control system	The relations between the dynamic domain and the control system are represented. The language of relations should however, be improved.	L
Help define what has to be shown to visualise how the control system is working by:		
- avoid black boxes and make control system activity transparent	The representation of the control system helps to specify user interface design requirements.	H
- show how algorithms work and explain the control system reasoning process	The control system can be described in the system representation and each algorithm can be represented with a sufficient level of detail.	H
Enable a collaborative approach by:		
- facilitating predictability of other team member actions	When taking the automatic control system as a team member, actions and intentions can be represented in relation to the goal of the work system. The human-human team aspect has to be further developed.	L
- defining a common frame of reference between the operator and the controlled system	System representation can work as a basis to develop a common frame of reference in design.	H
- defining the common goals between the operator and the controlled system	By defining the purpose, values and priorities in cells A1 and A2 in the matrix, common goals can be stated explicitly.	H

Requirements	Is the requirement fulfilled by the System Representation Matrix? Level of fulfilment: High (H), Low (L), None (N)	
SPECIFIC REQUIREMENTS (from Table 8)		
Dynamic domain		
- enable representation of the purpose(s) of the dynamic domain	In cell A1 the purpose(s) of the work system is (are) defined.	H
- enable representation of the physical objects in the dynamic domain	In cell A4 the physical structure in the work system is represented.	H
- enable representation of the functions of the dynamic domain	In cell A2 the functions in the work system are represented.	H
- enable representation of the dynamic behaviour	The entities, the relations and the system narrative combined can be used to reason about the dynamic behaviour.	L
Relation: Dynamic domain <=> Control system		
- define how control system activity is related to the dynamic domain's purposes, functions, physical structure and dynamic behaviour	The representation of the control system can be directly linked to a representation of the dynamic domain.	H
- identify and distinguish between different kinds of relations	The relations are defined by natural language. The possibility of collecting a set of relations for standard use needs to be developed further.	L
Control system		
- enable representation of goal(s) in relation to current status	The means-ends hierarchy enables representations that are event-independent, which makes it possible to model many system states.	H
- enable representation of available means to achieve the goal(s)	Goal achievement is represented by use of the means-ends hierarchy.	H
- enable representation of the control system(s) dynamic behaviour	By modelling relations and creating narratives, dynamic behaviour can be represented.	H
- aid in how to make control algorithms visible	Depending on the level of detail of the system representation, the algorithms can be explicitly visualised in the system representation matrix.	L
Relation: Control system <=> User interface		
- help defining what means are available for achieving a specific goal	By use of the means-ends hierarchy goal, achievement can be represented.	H
- help defining what data should be represented in the UI	By aggregating the representational needs from the context, the dynamic domain, and the control system relevant data can be chosen.	H

Requirements	Is the requirement fulfilled by the System Representation Matrix? Level of fulfilment: High (H), Low (L), None (N)	
- aid the choice of data to visualise for support of correct mental models.	See above. Presupposes a sufficiently adequate representation of the work system.	H
- aid pointing out where reliability of automatic functions have to be indicated	The fulfilment of this requirement has to be further developed.	N
Control system user interface		
- aid defining the UI information content (dynamic domain+control system)	By aggregating the representational needs from the representation matrix, the information content can be specified.	H
- aid defining the operator means for action in the UI	By aggregating the representational needs from the representation matrix, the operator means for action can be specified.	H
- aid defining how data can be integrated in the UI	By looking at the relation between functions, important relationships can be identified.	H
- aid defining how the operator can shift between multiple perspectives	By combining and representing different levels of abstraction in the interface, i.e. task-, function, process-, and object based information will improve the means for shifting perspective.	H
- aid defining where time should be explicitly visualised (history-now-projection)	By identifying entities with different time dependency, visualisation of time can be defined.	L
Relation: User interface <=> Operator		
- aid collaboration by pointing out where status and intentions of the operator and the control system can be made visible	Intentions are related to the goals in different situations. By making goals visible, the intentions can be inferred.	L
- aid defining how management of attention can be done in practice	No, this issue has to be further elaborated.	N
Operator		
- enable handling the trade-off between avoiding excess complexity without over simplifying	Finding the appropriate level of analysis is dependent on a clear formulation of the purpose of the analysis.	H
- support consistency in design	Detailed design guidelines have not been related to or developed within the method use as yet. There are however no known conflicts between use of the method and existing design guidelines.	N
- help defining necessary operator knowledge / competency	By aggregating the needs derived from each column in the representation matrix knowledge needs can be defined.	H

Requirements	Is the requirement fulfilled by the System Representation Matrix? Level of fulfilment: High (H), Low (L), None (N)	
SUPPORT DESIGN		
The method output should be design requirements useful for system design.	The fulfilment of this requirement needs further evaluation by using it in a complete development life cycle.	N
A method should work as a means to externalise knowledge.	The system representation can be used to elicit knowledge from different disciplines in a development project.	H
A method should support communication between participants.	System representation can work as a mediating object and a common frame of reference to support understanding and stimulate communication.	H
Making the representation directly readable by others, irrespective of background knowledge, to facilitate communication and knowledge transfer.	The system representation matrix can be read in natural language.	H
The method should facilitate taking other discipline's point of view.	The matrix columns invite taking the perspective of e.g. the process engineering-, control engineering-, user interface design-, and operator training professional.	H
The method should provide a way for a multidisciplinary team to communicate using a common language.	The system representation matrix provides a common frame of reference for different disciplines and thus has the potential to support collaboration and communication.	H
The method should support traceability of design requirements so that solutions can be traced back to the design decisions where the needs emerged.	Design decisions can be based on the needs derived from the system representation. The design requirements can then be referred to specific entities, relations or narratives in the system representation.	L
INDUSTRIAL VIABILITY		
The method should allow variability in how a method is used to allow adaptation to different industrial contexts.	The intention is that the method should be applicable in all types of control room contexts where automation is used. The method has to be applied in more contexts before drawing any conclusion about applicability in different domains. The boundaries of where the method is no longer applicable should be further explored.	L
The method should use terminology that can be understood by all stakeholders to facilitate communication and avoid misunderstandings	The method encourages use of natural language when describing relations between entities, which facilitates understanding compared to formal modelling languages.	H
The method should explicitly state what should be done and why. This requirement stresses the need for a pedagogical approach to method design	The method has been applied by others in with little personal guidance by the author, thus the method can be used based on the proposed instructions. However, there are still ambiguities in how to interpret what the cells in the	L

Requirements	Is the requirement fulfilled by the System Representation Matrix? Level of fulfilment: High (H), Low (L), None (N)	
	representation matrix can contain.	
The method should support the trade-off between efficiency and thoroughness by allowing for different levels of ambition in an analysis.	Finding the appropriate level of analysis is dependent on a clear formulation of the purpose of the analysis.	L
The method should produce the requirements needed to inform the HF design, but also give outputs in a format that are asked for by other stakeholders in later design stages.	There is a need for further evaluation of this criterion. The method has not been used in a full development cycle as yet.	N
The method should support identification of measurable indicators that can be used to assess and follow up system performance.	The values and priorities identified in the matrix can possibly be used as performance indicators.	L
The method should aim at being stimulating and meaningful for the individual participant, since this will improve intrinsic motivation and creativity.	The fulfilment of this need is difficult to assess. Judging from the small number of test participants the method can at least contribute to human factors engineering work, which would supposedly be meaningful for the intended users of the method.	L

In summary, when judging how well the requirements have been fulfilled, out of forty-six requirements, twenty-seven have reached a high level of fulfilment and fourteen have reached a low level of fulfilment. Five requirements have not been fulfilled at all. Given the requirements, the summary indicates there are potential benefits of the developed method, but that there are still both theoretical and practical aspects of the method that need further development. Two main themes can be extracted from the requirements that were rated as having low or no fulfilment. First, the relations between entities have to be made more explicit and clear. Second, the industrial viability requirements earned low ratings in general. This can be explained owing to having several aspects of the method that needed to be tested further in practical design projects, and throughout a development life cycle to be thoroughly evaluated.

8 Discussion

The discussion chapter first states the theoretical and methodological contributions of the research. This is followed by a discussion of threats to validity of the research work together with indications of the direction for further work.

8.1 Contributions

The thesis makes a theoretical and a methodological contribution. Here, the contribution is contrasted with existing research.

8.1.1 Theoretical contribution

The main theoretical contribution of this thesis is a theoretical unification of human-automation related challenges and a model used to describe the challenges systematically. In earlier research automation related challenges have been described as separate phenomena (see e.g. Andersson and Osvalder, 2009; Andersson, 2008; Bainbridge, 1983; Billings, 1996; Endsley and Kiris, 1995; Endsley et al., 2003; Lee and See, 2004; Lützhöft and Dekker, 2002; Moray and Inagaki, 2000; Moray, 2003; Parasuraman and Riley, 1997; Sarter et al., 1997; Wiener, 1989). The challenges can also interact and reinforce each other (Lee, 2006). However, there is no research presented so far as I know, that has provided a mapping of currently known automation related problems and described them in a unified way. The benefit of the unified descriptive model is that it provides a platform for building a systematic approach to address human-automation related challenges.

8.1.2 Methodological contribution

The methodological contribution of this thesis is a practice oriented approach with the ability to address human-automation related challenges. The approach can be applied for representation of automated human-machine systems. In comparison to other approaches with a similar purpose (Jamieson et al., 2012), i.e. lens model (Bisantz et al., 2000), finite state machines (Degani and Heymann, 2002; Heymann et al., 2001), applied cognitive work analysis (Elm et al., 2004, 2009, 2008, 2003), multilevel flow modelling (Lind, 2011a, 2011b, 2010; Rasmussen and Lind, 1982), and cognitive work analysis (Bisantz and Burns, 2009; Lintern, 2009; Naikar, 2011; Vicente, 1999), the approach presented in the thesis has been based on engineering needs rather than theory (Jamieson et al., 2012). The approach is similar to three of the approaches (Elm et al., 2004; Lind, 2011a; Vicente, 1999) in that it makes use of means-ends abstractions to describe socio-technical systems. The approach is also similar to one of the approaches (Lind, 2011a) in that it allows actions or tasks to be described in combination with the physical work domain and its control functions, which is not formally done in e.g. cognitive work analysis (Naikar, 2013; Vicente, 1999). The approach presented in the thesis is however, less formalised than the other frameworks and methods, although it attempts to squeeze the world into a matrix with the purpose of linking the system representation to the underlying model. In the comparison of five candidate frameworks for design of automated human-machine systems (Jamieson et al., 2012), an early version of the system representation matrix was identified as the only approach explicitly developed for human-automation interaction purposes, which strengthens the raison d'être of the approach presented in the thesis.

8.2 Threats to validity

The discussion will highlight the threats to the validity of the research by going through the thesis step by step. In this discussion validity is defined as the degree to which my research has studied what it intended to study (Kvale, 1995). In other words, if research is seen as a dartboard and human-automation challenges are at the centre, have I really hit the bull's eye? The discussion also indicates where further work is needed in relation to each part of the thesis.

The research problem

Research on automation related challenges are of interest considering the safety and performance issues reported from research within the area. The research focus is therefore an important concern.

The triadic semiotic model

The choice to use the triadic semiotic model proposed by Bennet and Flach (2011) was based on the pragmatic premises that it seemed to benefit the aim of representing human-automation challenges, rather better than a systematic search and comparison of different approaches. The pragmatic choice is potentially a threat to validity, since there might exist a better theoretical framework to describe and analyse human-automation challenges. Another threat to validity is if the triadic semiotic model is not capable of representing all the aspects relevant to the research problem. Several aspects of importance are, however, captured as described in chapter 2.3. But no model is omnipotent, and other approaches should work as complementary perspectives to provide a holistic view.

The extended triadic semiotic model

The next step was the expansion of the triadic semiotic model to cover process control. The three circles were expanded to four in order to separate the control system as a medium, into the control system and the control system interface. A question that arises is if the expansion really was necessary and if it was a mistake to move away from the original semiotic denominations. The meaning had not changed in my mind, but the difference between the semiotic model and the physical relations can potentially be confusing rather than clarifying, when abstract and physical concepts are mixed. The shift from semiotic to physical is probably the greatest threat to validity at this stage, with the risk of losing the meaning of Bennet & Flach's (2011) original model. The split of the 'medium' circle into control system and control system user interface was however, motivated by how the user interface is important to making automation understandable to the human.

Unification of how automation related problems can be described

The unification is potentially the greatest theoretical contribution in the thesis. When describing the automation related challenges as dynamic gaps, the explicit drawing of relations was sacrificed. In hindsight I believe this was a mistake that should be corrected in future work. I see the variation in the semiotic relations as the reason for the gaps emerging, but this is not explicit in the explications of the automation related problems in the model.

A foundational threat to validity is the accuracy of the assumption that incongruent variations create representational gaps. If that assumption is wrong or misleading the model basis has to be reconsidered. Still, it is possible that the model construction can lead to useful guidance to reduce practical problems without having to be fully scientifically correct. From a scientific point of view, the assumption should however, be tested empirically in future studies.

The gap model

One possible weakness of the gap model is the gaps can never be fully closed, which means it is difficult to use a gap as a measure of how severe an automation problem is. Rather, the gap model points out that despite that there being gaps, a system of human and machines can function appropriately (most systems work well after all). The fact that these systems work well despite gaps between how system parts represent each other, should further strengthen the importance of the human as a vital part in the system. The model could be used as an argument for the importance of taking human aspects into account, i.e. promote human factors engineering. It was stated that the human contributes the necessary adaptive capacity to handle incongruent variations. For human factors engineering design, this would mean that when we have reduced the gaps between systems parts as far as possible (not only between the human and the technical system); we should work to support operator adaptive capacity to meet variations that cannot be predicted. From the perspective of research validity, the gap concept is however, still somewhat elusive, and I believe it should be used as a model to guide thinking and action, rather than trying to use gaps as a measure of congruence.

Elicitation of method requirements

The theoretical unification of human-automation challenges was followed by an elicitation of method requirements. The requirements were collected both from theory and from interviews with human factors engineering practitioners. The requirements from theory came from several sources and domains, which strengthen their validity. A threat to validity in the interviews is the limited number of practitioners and the fact they were human factors persons, i.e. they already had a mind-set to the effect that the scope of the research field is important. Other respondents from other fields and professions would have improved the interview study. For example, including more people with a management background would have been beneficial to the relevance of the study, since respondents pointed out organisational aspects as a major obstacle for human factors engineering to reach a greater impact.

Methodification

In the methodification phase of the research work, the extended triadic semiotic model was merged with an abstraction hierarchy. The abstraction hierarchy has the potential to describe the dynamic domain, the control system, the control system interface and the operator knowledge in the same format. The abstraction hierarchy as used in Cognitive Systems Engineering, supports such unification, although the inclusion of the task level in my own hierarchy is controversial. It is however, necessary to represent action in relation to physical and functional constraints in order to make sense of automatic systems. This necessity encouraged me and my colleagues to pursue the idea, despite the theoretical critique to such an approach (Naikar, 2013). Other researchers with similar ideas, e.g. representing control system and work domain in the same model (Lind, 2011a), acknowledging that actors can influence constraints (Woltjer, 2005), using dual models to represent automation and work domain in parallel (Mazaeva and Bisantz, 2007) also strengthened our determination to test if tasks and scenarios could be efficiently represented along with a more traditional domain description.

The matrix provides a playing field where automated human-machine systems can be described. An iterative way of building a system representation of entities, relations and narratives was suggested. The validation of such a representation is complicated. The physical entities are easy for analysts to identify and agree on, as they exist in the physical world, but abstract functions are more complicated. Relations are even more elusive, since they can come in different forms and have different meanings. In this respect, Lind (2011b, 2011c) provides some guidance on action and control types, which should be explored further in future developments of the System Representation Matrix. Building narratives, that several subject matter experts can evaluate and suggest modifications to, is a possible way of validating a system representation. A practical difficulty using such an approach, is that it can be difficult to gather several experts from the same field of expertise. Performing the analysis of a particular system with diverse groups would however, strengthen the validity of a particular analysis. Those different groups of experts find different meanings in a system representation should be expected, since creation of narratives is dependent on working experience. Different persons will contribute with different perspectives.

The System Representation Matrix has been tested by different persons; by me and my colleague in the role of method developers, and by a small number of presumptive users. The matrix has also been applied to human-machine systems with different characteristics; it has during different stages in development, been used in the research team to describe a spoon, a microwave, a toaster, an adaptive cruise control, a feed water chloration subsystem and a paint factory batch process simulator. The method has also been used to represent human-automation related challenges discovered during simulator experiments with the paint factory simulator. For representation of automation related challenges specifically, the greatest threat to validity is that only the paint factory simulator has been tested. To improve validity, more examples have to be provided. The method has worked reasonably well with all systems tested this far, despite these being of varying character.

As was stated by the practitioners testing the method, it is a challenge to represent large systems with many entities and relations – and thereby many possible narratives. The System Representation Matrix's ability to create a system overview could be a benefit in this matter, to help different disciplines see the big picture and their own area of expertise as part of it. But representations also have to go into details, if representation is to be useful and lead to novel understanding and decisions. For example, a tool that let the analysts zoom in and out in a representation could be useful. Such a tool would allow for a fluent shift between levels of aggregation and detail and would aid dealing with complexity.

Through testing, it has been shown that users of the model believe the method is viable to their work as human factors engineering practitioners. Both strengths and weaknesses were identified. Despite weaknesses, none of the practitioners who have tested the method have considered it irrelevant or impossible to perform within the constraints of their daily work.

By testing the System Representation Matrix in various conditions, some degree of external validity (Shadish, 2002) has been achieved. Conclusions regarding generalizability of where and how the method can be used are however, difficult to make. Testing has been opportunistic, and made without categorising and comparing the test persons, the human-machine systems under analysis or the situations and scenarios included in the system representations. Threats to validity are still considerable in terms of the small number of participants, tests and tested systems on which the method has been applied. In general, validity and reliability is, to great extent, an issue for further research.

Testing of the System Representation Matrix was followed by an evaluation of method requirements. The level of fulfilment was assessed as high, low or no fulfilment. Assessments of the level of fulfilment were made by me alone, based on experiences from testing sessions where the System Representation Matrix was used. Performing the assessments alone is a threat to validity, and another assessor would have been beneficial. Assessments on a general level were made by assessing an average of how well the method fulfilled the requirements across tests. This is perhaps, not a threat to validity as such, but it does affect the specificity of the result and there is a risk of bias from me as a method developer. In the assessments I tried to be moderate and not skew the fulfilment of criteria to the positive end of the high-low-none scale, but to choose the lower part of the scale when such ambiguities arose.

Research process and approach

In the research process the roles of researcher, process engineer, user interface designer and operator were taken in the various projects. From the research perspective, the varying roles have improved validity of the research in general, in terms of creating something that is relevant and works in a specific context. It has provided opportunity to circle the research problem and view it from different perspectives. In general, the fact that research efforts have been performed in collaboration with fellow researchers is another factor that strengthens validity of the research. Neither have I been alone in the process of method development. The close collaboration with my fellow method developer strengthens the validity, as opposed to doing something like this alone. The current research has been performed using a practition centred approach. Kirlik (2012) suggested that situated but generalizable studies, in collaboration with practitioners, is a way of achieving both scientific understanding and usefulness in practice simultaneously. The situatedness of the research, prior to method development, has been strong in terms of background knowledge acquired in the multitude of projects in collaboration with both researchers and industrial practitioners. The results of method development (i.e. the work presented in the thesis), which have been performed in the context academia, are however, still weak in situatedness. To improve situatedness, the method has to be further tested with full scale socio-technical systems in real industrial projects with a full team of practitioners from different disciplines. Some steps in that direction have however, been taken. By continuing to develop the System Representation Matrix as an artefact subject to product development, it is my hope and intention that it will become useful to others in the future, in both research and practice.

9 Conclusions

Finally, the fulfilment of purpose and aim are summarised together with some general conclusions from the research work.

The purpose of the work presented in the thesis has been fulfilled by providing a model and a method that can aid creating an overview of automated human-machine systems. By generating a system overview human factors engineering practitioners can attain a unified view of human-automation challenges that has the potential to catalyse communication across disciplines involved in human factors related development work.

The first aim of the work has been met by theoretical unification of automation related challenges identified in existing research. The unification was achieved by extending a triadic-semiotic model and showing how several human-automation related challenges can be described in the same model. The second aim has been met by creating a method named the "System Representation Matrix". The System Representation Matrix has potential as an aid for reasoning about system functioning and design in automated human-machine systems.

Some general conclusions can be drawn based on the presented research:

- The main benefit of the System Representation Matrix is the ability to combine several aspects that are of importance for human factors engineering of automated human-machine systems. The System Representation Matrix integrates contextual factors, the dynamic domain, the control system, and the control system user interface and operator knowledge in a single format. The matrix enables seeing these system parts from physical and abstract perspectives and show how they are related to work tasks.

- The triadic semiotic model can be used as basis for assessing human-automation challenges in human factors engineering. It has been shown that the model can provide a unification of the human-automation related problems described in existing theory.

- Method development can be performed in iterations where the method is seen as an artefact. By iteratively testing and refining model based concepts, the System Representation Matrix has effectively evolved from an idea to a method that has been tested in the research team, with practitioners in an evaluation workshop as well as in a limited case in industrial human factors engineering practice.

- The developed System Representation Matrix can be used to create representations of automated human-machine systems. Representations are created by defining entities, establishing relations and creating system narratives in the matrix. The system representations can be used to describe system functioning, define knowledge needs and aid specification of design requirements.

- Based on evaluations it can be concluded that the System Representation Matrix has potential to become a viable tool for industrial use. In practice, the matrix could provide support for design decisions, help define necessary operator knowledge, and become a tool to aid human factors engineering in multidisciplinary teams.

References

Aesop, 500 B.C. Aesop's fables.
Ahl, V., Allen, T.F.H., 1996. Hierarchy theory : a vision, vocabulary, and epistemology. Columbia Univ. Press, New York.
Almefelt, L., 2005. Requirements-Driven Product Innovation - Methods and Tools Reflecting Industrial Needs (Doctoral thesis). Chalmers University of Technology.
Amabile, T.M., 1997. Motivating creativity in organizations: on doing what you love and loving what you do. California management review 40.
Amabile, T.M., 1998. How to kill creativity. Harvard Business School Publishing.
Amelink, M.H.J., 2010. Ecological Automation Design, Extending Work Domain Analysis (Doctoral thesis). TU Delft, Delft University of Technology.
Andersson, J., 2008. Levels of Automation and User Control - Evaluation of a Turbine Automation Interface (Report No. NKS-179). NKS - Nordisk Kärnsäkerhetsforskning.
Andersson, J., Bligård, L.-O., Osvalder, A.-L., Rissanen, M.J., Tripathi, S., 2011. To Develop Viable Human Factors Engineering Methods for Improved Industrial Use, in: Marcus, A. (Ed.), Design, User Experience, and Usability. Theory, Methods, Tools and Practice. Presented at the Human Computer Interaction International, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 355–362.
Andersson, J., Osvalder, A.-L., 2009. Levels of Automation and User Control in Use of an Automatic Turbine System. Presented at the European Conference on Cognitive Ergonomics 2009, Espoo, pp. 107–110.
Andersson, J., Osvalder, A.-L., 2013. Method characteristics for viable human factors engineering practice. Manuscript submitted to Applied Ergonomics.
Araujo, C.S., 2001. Acquisition of product development tools in industry: a theoretical contribution. Lyngby, Denmark, Technical University of Denmark.
Artman, H., 2000. Team situation assessment and information distribution. Ergonomics 43, 1111–1128.
Ashby, W.R., 1956. An introduction to cybernetics. Chapman & Hall, London.
Bainbridge, L., 1983. Ironies of automation. Automatica 19, 775–779. doi:10.1016/0005-1098(83)90046-8
Bennett, K.B., Flach, J.M., 2011. Display and Interface Design: Subtle Science, Exact Art. CRC Press, Hoboken.
Berlin, C., 2011. Ergonomics Infrastructure-An Organizational Roadmap to Improved Production Ergonomics. Chalmers University of Technology.
Berlin, C., Andersson, J., Fasth, Å., Grane, C., Abrahamsson, L., Johansson, J., Osvalder, A.-L., Stahre, J., 2012. Keyword Mingling workshop - a method for identifying and consolidating industrially perceived needs and requirements of future operators. Presented at the Swedish Production Symposium, SPS12.
Billings, C.E., 1996. Aviation Automation: Principles and Guidelines (No. NASA TechnicalMemorandum 110381). NASA Ames Research Center, Moffett Field, California.
Bisantz, A.M., Burns, C.M., 2009. Applications of cognitive work analysis. CRC Press, Boca Raton.
Bisantz, A.M., Kirlik, A., Gay, P., Phipps, D.A., Walker, N., Fisk, A.D., 2000. Modeling and analysis of a dynamic judgment task using a lens model approach. IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans 30, 605–616. doi:10.1109/3468.895884

Bligård, L.-O., 2011. Utvecklingsprocessen ur ett människa-maskinperspektiv. Chalmers University of Technology.
Bligård, L.-O., 2012. Predicting mismatches in user–artefact interaction. Development of an analytical methodology to support design work (Doctoral thesis). Chalmers University of Technology.
Boff, K.R., 1987. The tower of Babel revisited: On crossdisciplinary chokepoints in system design. System Design: Beehavioral perspectives on designers, tools, and organizations. New York: Elsevier.
Bolton, M.L., Bass, E.J., Siminiceanu, R.I., 2013. Using Formal Verification to Evaluate Human-Automation Interaction: A Review.
Branlat, M., Woods, D.D., 2010. How do systems manage their adaptive capacity to successfully handle disruptions? a resilience engineering perspective, in: 2010 AAAI Fall Symposium Series.
Brinkkemper, S., 1996. Method engineering: engineering of information systems development methods and tools. Information and Software Technology 38, 275–280. doi:10.1016/0950-5849(95)01059-9
Britannica Online Encyclopedia - automation [WWW Document], n.d. URL http://www.britannica.com/EBchecked/topic/44912/automation (accessed 2.5.14).
Brunswik, E., 1955. Representative design and probabilistic theory in a functional psychology. Psychological review 62, 193.
Burns, C.M., Hajdukiewicz, J.R., 2004. Ecological interface design. CRC Press, Boca Raton, Fla.
Chakraborty, S., Sarker, S., Sarker, S., 2010. An exploration into the process of requirements elicitation: a grounded approach. Journal of the Association for Information Systems 11, 212–249.
Christoffersen, K., Woods, D.D., 2002. How to make automated systems team players. Advances in Human Performance and Cognitive Engineering Research 2, 1–12.
Chung, A.Z., Shorrock, S.T., 2011. The research-practice relationship in ergonomics and human factors–surveying and bridging the gap. Ergonomics 54, 413–429.
Clark, D.C., Turk, M.A., 2013. The Future of Automation is Now!
Cockburn, A., 2002. Agile software development, The agile software development series. Addison-Wesley, Boston.
Cockton, G., Woolrych, A., 2002. Sale must end: should discount methods be cleared off HCI's shelves? interactions 9, 13–18.
Conant, R.C., Ashby, W.R., 1970. Every good regulator of a system must be a model of that system. International Journal of Systems Science 1, 89 – 97.
Cullen, L., 2007. Human factors integration – Bridging the gap between system designers and end-users: A case study. Safety Science 621–629. doi:10.1016/j.ssci.2007.01.002
Cummings, J.L., Teng, B.-S., 2003. Transferring R&D knowledge: the key factors affecting knowledge transfer success. Journal of Engineering and technology management 20, 39–68.
Degani, A., Heymann, M., 2002. Formal verification of human-automation interaction. Human Factors: The Journal of the Human Factors and Ergonomics Society 44, 28–43.
Dekker, S., Nyce, J., 2004. How can ergonomics influence design? Moving from research findings to future systems. Ergonomics 47, 1624–1639.
Dekker, S.W.A., Woods, D.D., 2002. MABA-MABA or Abracadabra? Progress on Human–Automation Co-ordination. Cognition Tech Work 4, 240–244. doi:10.1007/s101110200022

Duncan, K.D., Praetorius, N., 1992. Flow displays representing complex plant for diagnosis and process control. Reliability Engineering & System Safety 36, 239–244. doi:10.1016/0951-8320(92)90070-2

Elm, W., Roth, E., Potter, S., Gualtieri, J., Easter, J., 2004. Applied Cognitive Work Analysis (ACWA), in: Stanton, N., Hedge, A., Brookhuis, K., Salas, E., Hendrick, H. (Eds.), Handbook of Human Factors and Ergonomics Methods. CRC Press, pp. 36–1–36–9.

Elm, W.C., Gualtieri, J.W., McKenna, B.P., Tittle, J.S., Peffer, J.E., Szymczak, S.S., Grossman, J.B., 2008. Integrating cognitive systems engineering throughout the systems engineering process. Journal of Cognitive Engineering and Decision Making 2, 249–273.

Elm, W.C., Gualtieri, J.W., Tittle, J., Potter, S.S., McKenna, B., 2009. Pragmatic Use of Cognitive Work Analysis in System Design: Extending Current Thinking by Adapting the Mapping Principle, in: Bisantz, A.M., Burns, C.M. (Eds.), Applications of Cognitive Work Analysis. CRC Press, Boca Raton.

Elm, W.C., Potter, S.S., Gualtieri, J.W., Easter, J.R., Roth, E.M., 2003. Applied Cognitive Work Analysis: A Pragmatic Methodology for Designing Revolutionary Cognitive Affordances, in: Hollnagel, E. (Ed.), Handbook of Cognitive Task Design. Lawrence Erlbaum Publishers, Mahwah, N.J.

Endsley, M.R., 1995. Toward a theory of situation awareness in dynamic systems. Human Factors: The Journal of the Human Factors and Ergonomics Society 37, 32–64.

Endsley, M.R., Jones, D.G., Bolte, B., 2003. Designing for situation awareness. Taylor & Francis, London.

Endsley, M.R., Kiris, E.O., 1995. The out-of-the-loop performance problem and level of control in automation. Human Factors 37, 381–394.

Engelbrektsson, P., 2004. Enabling the user : exploring methodological effects on user requirements elicitation, Doktorsavhandlingar vid Chalmers tekniska högskola. Ny serie, 0346-718X ; 2172. Chalmers tekniska högskola, Göteborg.

Finger, R., Bisantz, A.M., 2002. Utilizing graphical formats to convey uncertainty in a decision-making task. Theoretical Issues in Ergonomics Science 3, 1–25. doi:10.1080/14639220110110324

Flach, J.M., 1995. Situation awareness: Proceed with caution. Human Factors: The Journal of the Human Factors and Ergonomics Society 37, 149–157.

Flach, J.M., 2012. Complexity: learning to muddle through. Cognition, Technology & Work 14, 187–197.

Frohm, J., 2008. Levels of Automation in Production Systems. Chalmers tekniska högskola.

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., Trow, M., 1994. The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies. SAGE.

Grix, D.J., 2010. The Foundations of Research. Palgrave Macmillan.

Guba, E.G., Lincoln, Y.S., 1994. Competing paradigms in qualitative research, in: Denzin, N.K., Lincoln, Y.S. (Eds.), Handbook of Qualitative Research. Sage Publications, Inc, Thousand Oaks, CA, US, pp. 105–117.

Henderson-Sellers, B., Ralyté, J., 2010. Situational method engineering: state-of-the-art review. Journal of Universal Computer Science 16, 424–478.

Heymann, M., Degani, A., Shafto, M., Meyer, G., 2001. On Abstractions and Simplifications in the Design of Human-Automation Interfaces (No. NASA/TM—2002–211397). Ames Research Center, Moffett Field, California.

Hoffman, R.R., Woods, D.D., 2011. Simon's Slice: Five Fundamental Tradeoffs that Bound the Performance of Human Work Systems, in: 10th International Conference on Naturalistic Decision Making, Orlando FL. pp. 5–31.

Hollender, M., 2010. Collaborative process automation systems. ISA, Research Triangle Park, NC.
Hollnagel, E., 1999. Modelling the controller of a process. Transactions of the Institute of Measurement and Control 21, 163–170.
Hollnagel, E., 2005. Joint cognitive systems: foundations of cognitive systems engineering. CRC Press, Boca Raton, FL.
Hollnagel, E., 2011. The Human in Control: Modelling What Goes Right Versus Modelling What Goes Wrong, in: Cacciabue, P.C., Hjälmdahl, M., Luedtke, A., Riccioli, C. (Eds.), Human Modelling in Assisted Transportation. Springer Milan, pp. 3–7.
Hollnagel, E., 2012. Coping with complexity: past, present and future. Cogn Tech Work 14, 199–205. doi:10.1007/s10111-011-0202-7
Hollnagel, E., Woods, D.D., 1983. Cognitive systems engineering: New wine in new bottles. International Journal of Man-Machine Studies 18, 583–600.
Hollnagel, E., Woods, D.D., 2005. Joint cognitive systems: foundations of cognitive systems engineering. CRC Press, Boca Raton, FL.
Hutchins, E., 1995. Cognition in the wild. MIT Press, Cambridge, Mass.
Introna, L.D., Whitley, E.A., 1997. Against method-ism: Exploring the limits of method. Information Technology & People 10, 31–45. doi:10.1108/09593849710166147
Jamieson, G.A., Andersson, J., Bisantz, A., Degani, A., Lind, M., 2012. Model-based approaches to human-automation systems design. Presented at the 2012 Proceedings of the ASME 11th Biennial Conference on Engineering Systems Design and Analysis (ESDA2012), pp. 871–880.
Jamieson, G.A., Miller, C.A., Ho, W.H., Vicente, K.J., 2007. Integrating Task- and Work Domain-Based Work Analyses in Ecological Interface Design: A Process Control Case Study. Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on 37, 887–905.
Jamieson, G.A., Vicente, K.J., 2005. Designing effective human-automation-plant interfaces: A control-theoretic perspective. Human Factors 47, 12–34.
Jämsä-Jounela, S.-L., 2007. Future trends in process automation. Annual Reviews in Control 31, 211–220. doi:10.1016/j.arcontrol.2007.08.003
Johnson, P., Duberley, J., 2000. Understanding Management Research: An Introduction to Epistemology. SAGE.
Jordan, P.W., 1998. An introduction to usability. Taylor & Francis, London.
Kirlik, A., 2012. Relevance versus generalization in cognitive engineering. Cogn Tech Work 14, 213–220. doi:10.1007/s10111-011-0204-5
Kirwan, B., 2000. Soft systems, hard lessons. Applied Ergonomics 31, 663–678. doi:10.1016/S0003-6870(00)00041-7
Klein, G., Feltovich, P.J., Bradshaw, J.M., Woods, D.D., 2005. Common Ground and Coordination in Joint Activity, in: Rouse, W.B., Boff, K.R. (Ed.), Organizational Simulation. John Wiley & Sons.
Klein, G., Woods, D.D., Bradshaw, J.M., Hoffman, R.R., Feltovich, P.J., 2004. Ten challenges for making automation a team player. Intelligent Systems, IEEE 19, 91–95.
Kvale, S., 1995. The Social Construction of Validity. Qualitative Inquiry 1, 19–40. doi:10.1177/107780049500100103
Lau, N., Skraaning Jr, G., Jamieson, G.A., 2009. Metacognition in Nuclear Process Control, in: Proc. of the 17th Triennial World Congress on Ergonomics [CD-Rom].
Lee, J.D., 2006. Human Factors and Ergonomics in Automation Design, in: Salvendy, G. (Ed.), Handbook of Human Factors and Ergonomics. John Wiley & Sons, Inc.
Lee, J.D., 2011. Automation: Friend or Foe? Ergonomics in Design: The Quarterly of Human Factors Applications 19, 31–32. doi:10.1177/1064804611411409

Lee, J.D., See, K.A., 2004. Trust in automation: Designing for appropriate reliance. Human Factors 46, 50–80.
Lind, M., 1994. Modeling goals and functions of complex industrial plants. Applied Artificial Intelligence an International Journal 8, 259–283.
Lind, M., 1999. Plant modelling for human supervisory control. Transactions of the Institute of Measurement and Control 21, 171–180.
Lind, M., 2009. Challenges to cognitive systems engineering: understanding qualitative aspects of control actions, in: European Conference on Cognitive Ergonomics: Designing beyond the Product—Understanding Activity and User Experience in Ubiquitous Environments. VTT Technical Research Centre of Finland, p. 1.
Lind, M., 2010. Foundations of Functional Modeling for Engineering Design Concepts of Means and Ends.
Lind, M., 2011a. An introduction to multilevel flow modeling. Nuclear safety and simulation 2, 22–32.
Lind, M., 2011b. Control functions in MFM: basic principles. Nuclear safety and simulation 2, 132–140.
Lind, M., 2011c. Reasoning about Causes and Consequences in Multilevel Flow Models. Presented at the 20th European Safety and Reliability Conference, ESREL.
Lintern, G., 2009. The Foundations and Pragmatics of Cognitive Work Analysis - A Systematic Approach to Design of Large Scale Information Systems. Cognitive Systems Design.
Lipták, B.G., 2006. Instrument engineers' handbook. Volume 2, Process control and optimization [Elektronisk resurs]. CRC Press, Boca Raton, FL.
Lützhöft, M.H., Dekker, S.W.A., 2002. On your watch: Automation on the bridge. Journal of Navigation 55, 83–96.
Mazaeva, N., Bisantz, A.M., 2007. On the representation of automation using a work domain analysis. Theoretical Issues in Ergonomics Science 8, 509–530. doi:10.1080/14639220600647816
Militello, L.G., Dominguez, C.O., Lintern, G., Klein, G., 2010. The role of cognitive systems engineering in the systems engineering design process. Systems Engineering 13, 261–273.
Moray, N., 2003. Monitoring, complacency, scepticism and eutactic behaviour. International Journal of Industrial Ergonomics 31, 175–178.
Moray, N., Inagaki, T., 2000. Attention and complacency. Theoretical Issues in Ergonomics Science 1, 354 – 365.
Mumaw, R.J., Roth, E.M., Vicente, K.J., Burns, C.M., 2000. There is more to monitoring a nuclear power plant than meets the eye. Human Factors 42, 36–55.
Naikar, N., 2011. Cognitive Work Analysis: Foundations, Extensions, and Challenges. DTIC Document.
Naikar, N., 2013. Work domain analysis: concepts, guidelines, and cases. CRC Press, Boca Raton.
Naikar, N., Hopcroft, R., Moylan, A., 2005. Work Domain Analysis: Theoretical Concepts and Methodology (No. DSTO-TR-1665). Victoria, Australia.
Neisser, U., 1976. Cognition and reality: principles and implications of cognitive psychology, A series of books in psychology, 99-0108656-6. Freeman, San Francisco.
Nemeth, C.P., 2012. Adapting to change and uncertainty. Cogn Tech Work 14, 183–186. doi:10.1007/s10111-011-0200-9
Nielsen, J., Hackos, J.T., 1993. Usability engineering. Academic press Boston.
Norman, D.A., 1993. Cognition in the head and in the world: An introduction to the special issue on situated action. Cognitive Science 17, 1–6.

Norman, D.A., 2010. Living with complexity. Mit Press.

Norros, L., Salo, L., 2009. Design of joint systems: a theoretical challenge for cognitive systems engineering. Cognition, Technology & Work 11, 43–56.

Novak, J.D., Cañas, A.J., 2008. The theory underlying concept maps and how to construct and use them. Florida Institute for Human and Machine Cognition, Pensacola.

NUTEK, 1996. DUP - resultat: driftutveckling inom processindustrin. Närings- och teknikutvecklingsverket (NUTEK).

O'Hara, J.M., Higgins, J.C., 2010. Human-system Interfaces to Automatic Systems:Review Guidance and Technical Basis (No. BNL-91017-2010). Brookhaven National Laboratory.

Osvalder, A.-L., Andersson, J., Bligård, L.-O., Alm, H., 2013. Impact of Physical Ergonomics Design of Process Control Rooms on Operator Experience of Comfort, Stress and Emotions (Report). Chalmers University of Technology.

Osvalder, A.-L., Bligård, L.-O., Andersson, J., Thunberg, A., 2011. Visualisering av anläggningsstatus - Utformning av innovativa gränssnittspresentationer (Report). Värmeforsk Service AB.

Parasuraman, R., Riley, V., 1997. Humans and automation: Use, misuse, disuse, abuse. Human Factors 39, 230–253.

Pew, R.W., Mavor, A.S., 2007. Human-system integration in the system development process: A new look. National Academics Press.

Rasmussen, J., 1979. On the Structure of Knowledge - a Morphology of Mental Models in a Man- Machine System Context.

Rasmussen, J., 1985. The role of hierarchical knowledge representation in decisionmaking and system management. IEEE Transactions on Systems, Man and Cybernetics 15, 234–243.

Rasmussen, J., 1986. Information processing and human-machine interaction : an approach to cognitive engineering, North-Holland series in system science and engineering, 99-0165010-0 ; 12. North-Holland, New York.

Rasmussen, J., Lind, M., 1982. A model of human decision making and its use for design of system control strategies (No. Riso-M-2349). Roskilde.

Rasmussen, J., Mark Pejtersen, A., Goodstein, L.P., 1994. Cognitive systems engineering, Wiley series in systems engineering, 99-1232417-X. Wiley, New York.

Reason, P., Bradbury, H., 2008. The SAGE handbook of action research : participative inquiry and practice. SAGE, Los Angeles.

Richardson, M., Ball, L.J., 2009. Internal representations, external representations and ergonomics: towards a theoretical integration. Theoretical Issues in Ergonomics Science 10, 335–376. doi:10.1080/14639220802368872

Rouse, W.B., 1985. On better mousetraps and basic research: Getting the applied world to the laboratory door. IEEE Transactions on Systems, Man and Cybernetics SMC-15, 2–8. doi:10.1109/TSMC.1985.6313389

Sarter, N., Woods, D.D., Billings, C.E., 1997. Automation Surprises, in: Salvendy, G. (Ed.), Handbook of Human Factors & Ergonomics. Wiley.

Sarter, N.B., Woods, D.D., 2000. Team play with a powerful and independent agent: A full-mission simulation study. Human Factors 42, 390–402.

Shadish, W.R., 2002. Experimental and quasi-experimental designs for generalized causal inference. Houghton Mifflin, Boston.

Sheridan, T.B., 2012. Supervisory Control, in: Salvendy, G. (Ed.), Handbook of Human Factors and Ergonomics. John Wiley & Sons, Inc.

Shu, Y., Furuta, K., 2005. An inference method of team situation awareness based on mutual awareness. Cognition, Technology & Work 7, 272–287.

Simon, H.A., 1962. The architecture of complexity. Proceedings of the American philosophical society 106, 467–482.
Simon, H.A., 1996. The Sciences of the Artificial. MIT Press.
Skyttner, L., 2005. General systems theory: problems, perspectives, practice. World scientific, Singapore.
Smith, K., Hancock, P.A., 1995. Situation awareness is adaptive, externally directed consciousness. Human Factors: The Journal of the Human Factors and Ergonomics Society 37, 137–148.
Stanton, N.A., Salmon, P.M., Walker, G.H., Baber, C., Jenkins, D.P., 2005. Human factors methods: a practical guide for engineering and design. Ashgate Publishing, Ltd.
Stevenson, A. (Ed.), 2010. Oxford dictionary of English. Oxford University Press, New York, NY.
Svensson, L., 1986. Grupper och kollektiv : en undersökning av hemtjänstens organisation i två kommuner, Utredningsrapport / Arbetslivscentrum, 0282-9096 ; 2. Arbetslivscentrum :, Stockholm.
Svensson, L., 2002. Interaktiv forskning - för utveckling av teori och praktik, Arbetsliv i omvandling. Arbetslivsinstitutet.
Svensson, L., Aronsson, C., Höglund, S., 1990. Kan byråkratin förändras? Ordfront, Stockholm.
Theberge, N., Neumann, W.P., 2010. Doing “organizational work”: Expanding the conception of professional practice in ergonomics. Applied Ergonomics 42, 76–84. doi:10.1016/j.apergo.2010.05.002
Thoresson, A., 2010. It-system trimmar industrins utsläpp. Dagens Industri.
Ulrich, K.T., Eppinger, S.D., 2004. Product design and development. McGraw-Hill, Boston.
Vicente, K.J., 1999. Cognitive work analysis : toward safe, productive, and healthy computer-based work. Lawrence Erlbaum Associates, Mahwah, N.J.
Vicente, K.J., Burns, C.M., Pawlak, W.S., 1993. Egg-sucking, mousetraps, and the tower of Babel: Making human factors guidance more accessible to designers (No. CEL 93-1). Toronto, Canada: Cognitive Engineering Laboratory, University of Toronto.
Vicente, K.J., Mumaw, R.J., Roth, E.M., 2004. Operator monitoring in a complex dynamic work environment: a qualitative cognitive model based on field observations. Theoretical Issues in Ergonomics Science 5, 359–384. doi:10.1080/14039220412331298929
Vicente, K.J., Rasmussen, J., 1992. Ecological interface design: Theoretical foundations. IEEE Transactions on Systems, Man and Cybernetics 22, 589–606.
Waterson, P., Kolose, S.L., 2010. Exploring the social and organisational aspects of human factors integration: A framework and case study. Safety Science 48, 482–490. doi:10.1016/j.ssci.2009.12.018
Westrenen, F., Praetorius, G., 2012. Maritime traffic management: a need for central coordination? Cognition, Technology & Work 16, 59–70. doi:10.1007/s10111-012-0244-5
Wiener, E.L., 1989. Human Factors of Advanced Technology (“Glass Cockpit”) Transport Aircraft (No. Report 177258), NASA Report.
Woltjer, R., 2005. On how constraints shape action, Linköping studies in science and technology. Thesis, 0280-7971 ; 1221. Univ., Linköping.
Woods, D., 2005. Generic support requirements for cognitive work: laws that govern cognitive work in action, in: Proceedings of the Human Factors and Ergonomics Society Annual Meeting. SAGE Publications, pp. 317–321.
Woods, D.D., 1984. Visual momentum: a concept to improve the cognitive coupling of person and computer. International Journal of Man-Machine Studies 21, 229–244.

Woods, D.D., Branlat, M., 2011. How human adaptive systems balance fundamental trade-offs: Implications for polycentric governance architectures, in: Proceedings of the Fourth Resilience Engineering Symposium, Sophia Antipolis, France.

Woods, D.D., Christoffersen, K., 2002. Balancing practice-centered research and design. Cognitive Systems Engineering in Military Aviation Domains. Wright-Patterson AFB, OH: Human Systems Information Analysis Center 121–136.

Woods, D.D., Hollnagel, E., 2006. Joint cognitive systems: patterns in cognitive systems engineering. CRC/Taylor & Francis, Boca Raton:

Woods, D.D., Patterson, E.S., Roth, E.M., 2002. Can We Ever Escape from Data Overload? A Cognitive Systems Diagnosis. Cognition, Technology & Work 4, 22–36.

Woods, D.D., Sarter, N., 2000. Learning from automation surprises and "Going Sour'' accidents, in: Amalberti, N.B.S. and R. (Ed.), Cognitive Engineering in the Aviation Domain. Mahwah, N.J.: Lawrence Erlbaum Associates.