Train operation in the future: Development of a psychological instrument for an optimal design of future human-machine systems in railway operation

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Abstract:

Increasing digitization and automation of train control at the Swiss Federal Railways (SBB) are going to change work processes radically. So, a number of questions arise that will be of decisive importance for the cost-effectiveness, safety and reliability of train control in the future: How can we make use of the advantages of automation without trapping into the pitfalls of their "ironies" [1]? How can we design work processes prospectively such that we will not be surprised by future technical developments? How can we use the positive aspects of automation while mitigating its negative consequences, and finally, how can we ensure the safety and reliability of the railway system in the future? A joint research project between the University of Applied Psychology and the Swiss Federal Railways should provide answers to these questions. The aim of the project was to develop a catalogue of requirements, theoretically founded by work psychology, which would allow developers to design automated systems such that human-machine interaction would not lead to losses of operators' situation awareness or his or her competences and abilities. In order to develop these requirements, we conducted expert workshops on the date basis of previously carried out work analyses of the human-machine systems of train drivers. In these expert workshops with totally 14 participants (train drivers, fleet procurement, shunting, security specialist) we specified recommendations for future automation projects. These requirements were theoretically founded by a specific psychological method for the analysis, evaluation and design of human-machine systems, called KOMPASS [3]. General aim of KOMPASS and of the psychological requirements was to offer the operator control over the human-machine system and to design automated systems such that operators can maintain control over the automated system. Finally, we put these requirements into an electronic instrument, which should be used by developers to embed work-related psychological requirements in the design of automated human-machine systems. The instrument helps the developer to identify and to justify psychological requirements at an early stage of technology development, where there is still a relatively large amount of formative scope of action. Actually, Swiss Federal Railways use the instrument for the optimal design of train control as well as for an optimal design of future rail traffic management systems.

Keywords: automation, human-machine system, work psychology, rail traffic

Introduction

Modern work systems are in general complex human-machine systems (MMS). An important aspect of the design of such work systems is the task allocation between human and machine. This aspect is becoming increasingly important, especially due to the growing automation in the last years. Automation systems can lead to problems, who can have an impact on the reliability of the whole human-machine system [5].

Increasing digitization and automation of train control at the Swiss Federal Railways (SBB) are going to change work processes radically. This change also affects the working environment of the train drivers, the driver's cab. Drivers do their job in an increasingly automated environment. In December 2017, for example, the SBB carried out a test in which a train automatically braked and accelerated [2]. But nowadays, trains are by no means unaccompanied or self-propelled. The tasks of the train driver will remain, but they will change as a result of increasing automation. Therefore, a prospective design of drivers´ work processes is essential to use the positive aspects of automation while mitigating its negative consequences. How can we make use of the advantages of automation without trapping into the pitfalls of their "ironies" [1]? How can we design work processes prospectively such that we will not be surprised by future technical developments? How can we use the positive aspects of automation while mitigating its negative consequences, and finally, how can we ensure the safety and reliability of the railway system in the future?

Research purpose
The general aim of the project was to develop a catalogue of requirements, theoretically founded by work psychology, which would allow developers to design automated systems such that human-machine interaction would not lead to losses of operators' situation awareness or his or her competences and abilities. This was the first part of the project. In a second part, we implemented the requirements in an electronic instrument and then tested it for usability and comprehensibility. This report follows this structure. The first part of this report describes the identifying psychological requirements for human-machine system design, the second part the implementing of the requirements in an electronic tool.

PART I – IDENTIFYING PSYCHOLOGICAL REQUIREMENTS FOR HUMAN-MACHINE SYSTEM DESIGN

Modern work systems and negative consequences of automation

Modern work systems are often complex human-machine systems. Different people cooperate and work together with technical systems to fulfill given tasks [5]. In railway operations as well as in train control, for example, such modern work systems require mainly to monitor and to control automated processes and parameters. When designing work tasks in automated work systems, the human-machine division of functions, the individual work task and the work system into which human and technology are organizationally embedded must be taken into account [7]. A central aspect of this is the functional allocation between human and machine. In this context, certain principles for the psychological design of work activities should be implemented such that people can fulfil their work tasks in the best possible way. Hacker [4] calls among other things the *completeness of the task.* Human should not carry out monitoring tasks only, but also planning activities, preparation and control tasks. *Transparency,* another principle according to Hacker [4], means the process transparency of a human-machine system with opportunities for forming and maintaining mental models of production processes and its integration into the overall context. These design principles are not easy to realize, especially in automated monitoring systems. If an appropriate functional allocation fails, negative consequences will occur [5].
There are three major problem areas in case of a suboptimal interaction between human and automation: a lack of confidence or excessive trust in automation, difficulties in maintaining adequate situational awareness and the loss of skills due to the use of automated systems [5]. These possible negative consequences must be avoided or mitigated. One way to do this is the use of specific work psychological design criteria. The KOMPASS method [3] entails such criteria.

Criteria of the KOMPASS method

The KOMPASS method was initially developed for the analysis, evaluation and design of automated production systems. It derives from theories of work psychology, which are relevant for a human-centered design of the work system, the work activity and the human-machine function division. The criteria are *process transparency, dynamic coupling, decision authority* with *information authority and execution authority, flexibility.* A brief description of these criteria follows:

- *Process transparency.* The goal of transparent processes is to enable employees to understand the processes in progress. However, the processes are often not visible to the operator and therefore difficult to see through. Process transparency is achieved by *active interaction* of the operators with the system, *direct feedback* from the system via various sensory channels and *knowledge of the feedback channels.*
- *Dynamic coupling.* In automated work systems, the influence of operators is often limited and the execution of tasks is strongly dependent on the process. Through a dynamic connection to the technical system, operators should be able to influence processes and thus have the opportunity to act according to the situation. A dynamic coupling is achieved by giving the task execution options with *regard to time, procedure* and the necessary *attention.*
- *Information authority.* If the operator has the authority over the flow of information, he or she is enabled to actively search for and record information about the process. This is achieved by allowing operators to retrieve information from the process and change information filters at any time. The aim of *information recording* is to determine how the (accessible) information is presented. The degree of automation of *information processing* refers to the extent to which the interpretation of system states is taken over either by the technology or the operator.

- *Execution authority.* The goal of the execution authority is that operators can actively and positively influence safety and productivity by providing opportunities for influencing and controlling processes. This includes the independent *making of decisions* on processes and procedures as well as control over the *execution of actions* and process control per se.
- *Flexibility.* A flexible allocation of authority between the operator and the technical system allows the operator to build up know-how, to gain experience and to react to faults in a competent way. In *adaptable automation,* it is the operator who determines the function assignment to the machine (e. g. switching to a technical assistant). In the case of *adaptive automation,* the functions are assigned by the technical system on the basis of defined criteria (e. g. when the human being reacts too slowly, in case of decreasing performance or under specific situational conditions).

For practical design requirements in a specific working context, such as in railway operations, the KOMPASS criteria must be derived and specified.

Operationalization of the KOMPASS criteria

Job environment of the train drivers

The requirements to be developed should enable the design of human-machine systems of the train drivers by the SBB. Therefore, the subject of the analysis was the tasks of the train driver in the driver's cab (see figure 1) with the train drivers and shunters as primary target groups.

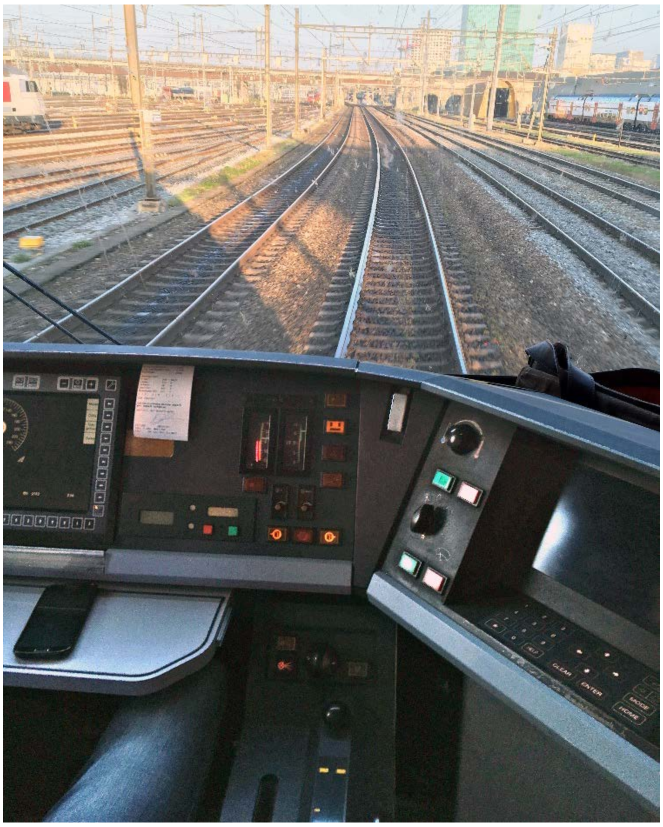

Figure 1: View from a driver's cab (separate photo)

The tasks of train drivers in normal operation are guiding the train in the driver's cab and monitor all instruments and displays. At the same time, they concentrate on the route, the timetable and the weather. In a constantly changing environment, they react quickly and correctly to signals, speed controls and unforeseeable events. They act independently but are in constant contact with stations, control centers and other offices. Before the train drivers can pilot in the driver's cab of the locomotive, they must be ready for operation. This means that they gather information about construction sites, changes to the work plan or extra services [6].

Procedure

On the basis of previously conducted work analyses of the human-machine system of train drivers with observations and interviews, we conducted expert workshops to operationalize the compass criteria. In order to be able to operationalize the KOMPASS criteria more precisely, we have divided them into their sub-content: *active interaction* and *feedback* (Process transparency), *user-integrating design* and *variable binding to workflows* (dynamic coupling), *information recording* and *information processing* (information authority), *decision making* and *action execution* (execution authority), *adaptable automation* and *adaptive automation* (flexibility). These labels of the criteria will be used in this report from now on.

What are the main tasks train drivers will have to carry out in the future? Together with experts we identified the target status of the human-machine system with this fundamental question. Divided into two workshops, fourteen experts (train drivers, fleet procurement, shunting, security specialist) discussed specific questions based on the KOMPASS criteria (in brackets):

- *What does the train driver need in order to actively deal with the system (technical processes, workflows, situation)?* (active interaction)
- *What kind of feedback from the technology or other persons does the train driver need?* (feedback).
- *What does the train driver need in order to make decisions on procedures and workflows as well as possible?* (decision making)
- *What does the train driver need in order to be able to carry out activities himself?* (action execution)
- *When and for which tasks should the technical system or the train driver decide whether the task is to be performed by the train driver or by the technology?* (adaptive automation)

Based on the answers of the experts, we, the work psychologist, identified technical requirements on a human-machine system as well as requirements regarding education and training and requirements regarding organizational processes. Figure 2 shows the procedure by way of an exemplary answer from the train drivers to one of the questions in the expert workshop. Additionally (but not shown in Figure 2), we identified risks that may arise if a requirement cannot be applied. Furthermore, we defined possible compensations for this case.

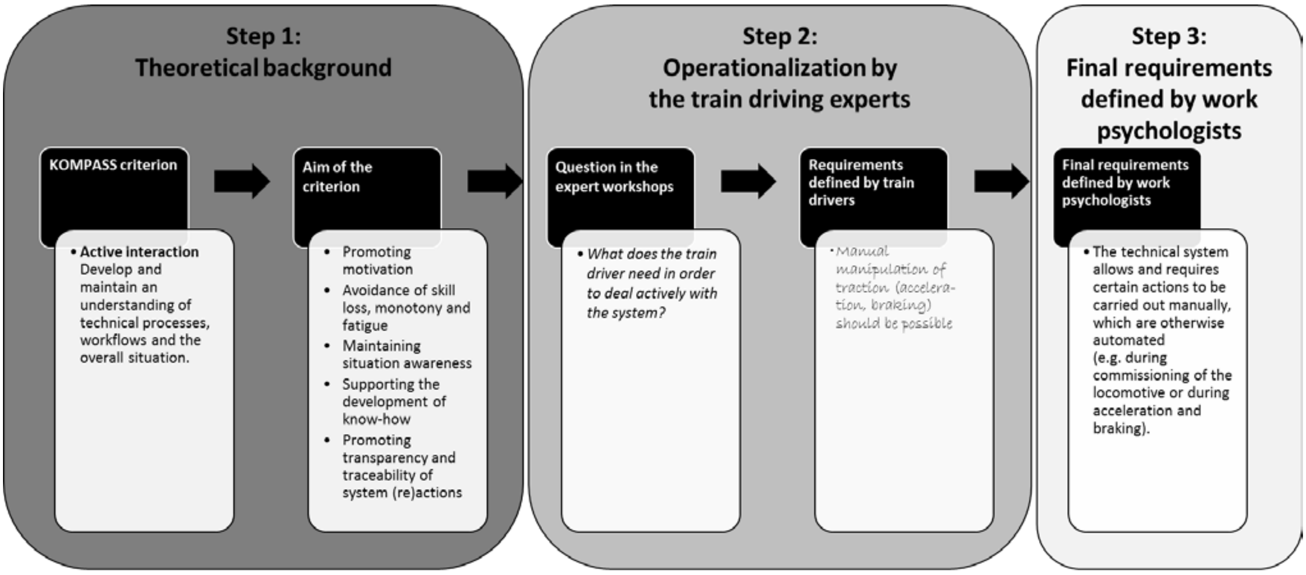

Figure 2: Procedure for the operationalization of the KOMPASS criteria

Resulting requirements

The result is a catalogue with 88 requirements, defined regarding to technology (64), education and training (14) and organizational processes (10). Table 1 shows a few examples of the resulting requirements.

How do you use these requirements in practice? If a new technical system in the working environment of the train drivers is planned, the responsible persons in the project will process the requirements and determine the need for action. In order to make this processing of the requirements manageable, the requirements must be implemented into an electronic tool.

Table 1: Examples of requirements for a human-machine system regarding to technology, education and training as well as regarding to organizational processes based on the KOMPASS criteria

KOMPASS criterion	Requirement	Aim of the requirement
Active interaction. Develop and maintain an understanding of technical processes, workflows and the overall situation.	The technical system makes it possible and requires certain actions to be carried out manually, which are otherwise automated (e.g. during commissioning of the locomotive or during acceleration and braking).	▪ Promoting motivation ▪ Avoidance of skill loss, monotony and fatigue ▪ Maintaining situation awareness ▪ Supporting the development of railway know-how ▪ Promoting transparency and traceability of system (re)actions
	The training imparts system-specific knowledge of procedures and processes used during incidents.	▪ Adequate response to disruptions ▪ Promoting competence development Supporting knowledge building ▪ Promoting an understanding of the work processes
Feedback. Develop and maintain an understanding of technical processes, workflows and the overall situation.	The technical system provides prompt feedback on the actions performed by the operator; indication of longer response times by corresponding messages.	▪ Understanding of the work processes ▪ Supporting the fulfilment of tasks ▪ Avoidance of (cognitive) overload ▪ (process) control
	Practice the interpretation and identification of error messages in the training. Enable the operators to recognize which error messages are relevant and how they must react to them.	▪ Supporting knowledge building ▪ Promoting transparency and traceability of system (re)actions
	Ensure the transfer of all relevant information between train preparation and control.	▪ Holistic situation perception ▪ Error prevention ▪ Supporting the fulfilment of tasks
Execution of action. Execution remains with the operator, serves to build up and maintain knowledge, skills and expertise.	The technical system enables the operator to adapt the driving behaviour to the respective conditions (weather, rail condition, etc.).	▪ Promoting motivation ▪ Avoidance of skill loss ▪ Maintaining situation awareness
	Ensure the training of rarely used technical systems and functions that might be critical during an incident	▪ Promoting competence development ▪ Supporting knowledge building ▪ (process) control ▪ Adequate response to incidents

PART II: IMPLEMENTING THE REQUIREMENTS IN AN ELECTRONIC TOOL AND TESTING

Implementing

The general aim of the project was to develop a catalogue of requirements, theoretically founded by work psychology, which would allow developers to design automated systems for train drivers such that human-machine interaction would not lead to losses of operators' situation awareness or his or her competences and abilities. In the second part of the project, we implemented the requirements in an electronic tool. The electronic tool had to meet the following needs:

- it should be usable without additional software;
- it should be easily usable for employees of a company;
- it should be easily modifiable, e.g. names of organizational units must be changeable;
- it should provide filtering options;
- it should be usable for several people to work on the instrument and it must be stored centrally.

According to the needs, we decided to realize the electronic tool in Excel, enhanced with macros. The practice partner and we developed *use cases* in which we clarified the question of who should use the instrument (roles, departments), for which tasks/projects and at which point in the process the instrument is going to be used. We described the *use cases* in a generic implementation guide for the company and developed as well a training course for the use of the tool.

Testing

In our next step, we are going to test the instrument together with rail experts. In this pilot, users apply the instrument to a concrete practical project in the railway industry and we can test the instrument for comprehensibility and manageability.

Discussion

The aim of the project was to develop a catalogue of requirements, theoretically founded by work psychology. This catalogue of requirements would allow developers to design automated systems such that human-machine interaction would not lead to losses of operators' situation awareness or his or her competences and abilities. The developed requirements are implemented in the form of an excel-based electronic instrument, enhanced with macros.
From a critical point of view, it could be argued that nothing new has emerged in this research and development project. The results, the developed requirements, contain the not new realization that automated systems should keep humans in control and follow the premise of humans as ultimate responsible agents within a human-machine system. On the one hand, is it true, we based this research on a well-known theoretical background by using the criteria of the KOMPASS method as a basis. However, new is the operationalized and practical requirements for technical systems in rail traffic regarding to technology, to education and training as well as to and organizational processes. The requirements are based on the well-known requirements for an automated system but map the specific tasks of train drivers.
However, these results are specific for the railway operation. For a use in other socio-technical contexts, i.e. aviation, they have to be adopted to the specific work requirements.

Conclusions

Digitization and automation are increasing and fully automatic train control will probably be implemented in foreseeable future. Current experiments point in this direction (see [2]). What full automation means for people and their work are central questions that work psychology has to deal with. Nevertheless, this project aims at the design of technical systems in which humans play or have to play an active role. Full automation may come, but only in a few years' time. In the meantime, it is important to design technical systems such that people can perform their satisfying tasks safely and reliably.

References

[1] Bainbridge, L. (1983). Ironies of Automation. *Automatica, 19,* 775-779.

[2] Balande, K. (2017, decembre 5). *Automatisch, aber mit Lokführer.* Retrieved from https://dima.sbb.ch/unterwegs/artikel/68833/automatisch-aber-mit-lokfuehrer

[3] Grote, G., Wäfler, T., Ryser, C., Weik, S., Zölch, M. & Windischer, A. (1999). *Wie sich Mensch und Technik sinnvoll ergänzen. Die ANALYSE automatisierter Produktionssysteme mit KOMPASS.* Schriftenreihe Mensch-Technik-Organisation (Hrsg. E. Ulich), Band 19. Zürich: vdf Hochschulverlag.

[4] Hacker, W. (1989). Vollständige vs. unvollständige Arbeitstätigkeiten. In S. Greif, H. Holling & N. Nicholson (Hrsg.), *Arbeits- und Organisationspsychologie. Internationales Handbuch in Schlüsselbegriffen* (S. 463–466). München: Psychologie Verlags Union.

[5] Manzey, D. (2012). Systemgestaltung und Automatisierung. In P. Badke-Schaub, G. Hofinger & K. Lauche (Hrsg.), *Human Factors. Psychologie sicheren Handelns in Risikobranchen. 2. Aufl.* (S. 333–352). Berlin Heidelberg: Springer

[6] SBB (2017, decembre 5). *Der Beruf Lokführer/-in.* Retrived from https://company.sbb.ch/de/jobs-karriere/berufserfahrene/zweitausbildungen/lokfuehrerin/beruf.html

[7] Wäfler, T., Windischer, A., Ryser, C., Weik, S. & Grote, G. (1999). *Wie sich Mensch und Technik sinnvoll ergänzen. Die GESTALTUNG automatisierter Produktionssysteme mit KOMPASS.* Schriftenreihe Mensch-Technik-Organisation (Hrsg. E. Ulich), Band 18. Zürich: Hochschulverlag an der ETH Zürich.