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Human-Automation Teamwork

CURRENT PRACTICES AND FUTURE DIRECTIONS IN AIR TRAFFIC CONTROL

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Current Practices and Future Directions in Air Traffic Control

by

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ABSTRACT

This dissertation explores the topic of human-automation teamwork in Air Traffic Control (ATC). ATC is a high stakes environment where complex automation is being introduced while the human operator has the legal responsibility. With increasing demands on productivity in various industries (as also in ATC), automation is introduced for efficiency, maintaining safety, and to keep the workload of the human operator within acceptable limits. However, previous research has shown that automation may cause negative effects on the human operator and performance, such as forcing the operator out of the control loop, which might lead to problems or confusion. Previous research suggests a need for strengthening human-automation collaboration where automation is seen as a team member to keep the operator in the loop. In order to achieve such teamwork, the design of the automation needs to be human-centred, i.e. that the automation is designed for the underlying need of the operator.

The aim of this dissertation is to explore teamwork in ATC from several angles to understand how the air traffic controllers are working in current ATC environments and how automation could be designed to support human-automation teamwork. The included studies rely on interviews, simulations, and questionnaires, all with operational air traffic controllers as participants.

The results indicate that for both human-human teamwork and human-automation teamwork, teamwork factors such as adaptability and mutual performance monitoring (knowing what the other team members are doing) are important for the work performance in current ATC environments, where mutual performance monitoring is especially important during stressful situations.

When designing automation, lessons learned from human-human teamwork should be considered. The work within the scope of this dissertation identifies and concerns two human-automation teamwork aspects: boundary awareness and implicit communication. These are proposed to support the operator’s knowledge about the automation and the communication flow between the operator and the automation. Boundary awareness is the operator's knowledge of the automation's abilities, its boundaries (what it can or cannot manage), and about consequences if it would go outside of these boundaries. Implicit communication is the unspoken or implied small cues that the operator and the automation can use to communicate with each other. It is proposed that implicit communication can be based on the work patterns of the operator. The knowledge gained through the work in this dissertation can be used as a foundation for further research and design of automation regarding operator knowledge about the automation boundaries and the communication within the team.

SVENSK SAMMANFATTNING

Denna avhandling utforskar teamwork mellan människa och automation inom flygtrafikledning. Flygtrafikledning är en högriskmiljö där komplex automation introduceras samtidigt som den mänskliga operatören har det juridiska ansvaret. Med ökade krav på produktivitet inom olika industrier (och även inom flygtrafikledning) så introduceras automation för effektiviteten, för att bibehålla säkerheten och för att hålla arbetsbelastningen för den mänskliga operatören inom acceptabla gränser. Tidigare forskning har däremot visat att automationen kan orsaka negativa effekter på den mänskliga operatören och på prestationen, som till exempel att tvinga ut operatören utanför kontrolloopen vilket leder till problem och förvirring. Tidigare forskning föreslår ett starkare samarbete mellan människa och automation där automationen är sedd som en teammedlem för att behålla operatören i loopen. För att uppnå ett sådant samarbete behöver automation vara människo-centrerad, att automation med andra ord är designad för operatörens underliggande behov.

Syftet med denna avhandling är att utforska teamwork från olika vinklar inom flygtrafikledning för att förstå hur flygledare jobbar i nuvarande flygtrafikledningsmiljöer och för att förstå hur automation skulle kunna designas för att stödja teamwork mellan människa och automation. Studierna som denna avhandling bygger på har använt sig av intervjuer, simuleringar och enkäter, alla med operativa flygtrafikledare som deltagare.

Resultatet tyder på att för både människa-människa teamwork och människa-automations teamwork så är teamwork faktorer så som flexibilitet och ömsesidig övervakning av teammedlemmarnas prestationer viktiga där övervakning av teammedlemmarnas prestationer är speciellt viktigt under stressiga situationer.

När man designar automation bör man ta lärdom från teamwork mellan människor. Vidare så identifierar och behandlar arbetet inom denna avhandling två aspekter gällande teamwork mellan människa och automation: gränsmedvetenhet och implicit kommunikation. Dessa aspekter är föreslagna att stötta operatörens kunskap om automationen och kommunikationsflödet mellan operatören och automationen. Gränsmedvetenhet är operatörens kunskap om automationens förmågor, dess gränser och dess konsekvenser när automation går utanför dessa gränser. Implicit kommunikation är de outtalade eller implicita ledtrådar som operatören och automationen kan använda för att kommunicera med varandra. Det är föreslaget att implicit kommunikation kan baseras på arbetsmönster från operatören eller från prediktioner från automationen. Kunskapen från denna avhandling kan användas som ett underlag för vidare forskning och design av automation gällande operatörers kunskap om automationens gränser och kommunikationen inom teamet.

INCLUDED PUBLICATIONS

Paper I

Svensson, Å., Ohlander, U., & Lundberg, J. (2019). **Design implications for teamwork in ATC**. Cognition, Technology & Work. doi:10.1007/s10111-019-00579-y.

Paper II

Svensson, Å., Lundberg, J., Forsell, C., & Rönnberg, N. **Automation, teamwork, and the feared loss of safety – Air traffic controllers' experiences and expectations on current and future ATM systems**. Submitted to ECCE2020: European Conference on Cognitive Ergonomics.

Paper III

Svensson, Å., Forsell, C., Johansson, J., & Lundberg, J. (2017). **Analysis of work patterns as a foundation for human-automation communication in multiple remote towers**. In Proceedings of the Air Traffic Management Research and Development Seminar, Seattle, Washington, USA.

Paper IV

Svensson, Å., Lundberg, J., Forsell, C., Rönnberg, N., & Alfredson, J. **Boundary Awareness and Automation Degradation: Realistic human-automation work episodes in air traffic control**. Submitted to the Journal of Cognitive Engineering and Decision Making.

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1. INTRODUCTION

Automation support is introduced in various industries to meet the demands of higher productivity. Human operators are expected to collaborate with the automation, similar to the collaboration with a human team member. Good human-automation collaboration is fundamental for maintaining safety and retaining the human operator's final authority, particularly in high stakes environments like Air Traffic Control (ATC). To achieve such collaboration, researchers have for a long time argued for designing automation after human-centred design principles (C. E. Billings, 1991), i.e. the automation should be designed to meet the needs and requirements of the operator.

The aim of this dissertation is to explore human-human and human-automation teamwork within the domain of ATC from a human factors design perspective. One reason for exploring human-automation teamwork is that teamwork is essential for maintaining safety and enhancing performance, which are two of the major reasons for introducing automation in the first place. The focus of having a human factors design perspective is to support cognitive work for Air Traffic Controllers (ATCOs) when working with automation. This to be able to meet the increased demands on efficiency while maintaining high safety. As long as there is a cognitive system (Hollnagel & Woods, 1983) with both humans and automation, there needs to be human-automation teamwork where the human operator has knowledge about the automation and can work closely with it and vice versa.

ATC is, and will for a foreseeable future be, a domain where humans are highly involved in traffic management decisions. The ATCOs are monitoring, approving, and adjusting individual aircraft trajectories in direction, speed, and altitude. Even though current levels of automation are rather low, it is also a domain where higher degrees of automation are being considered, with a major ongoing effort in research and design. Potentially, new automation can shift human operators from specific traffic adjustments, toward other traffic management roles and tasks.

The purpose of the ATC service, and the responsibility of the ATCO, is to prevent collisions between multiple aircraft and between aircraft and obstructions on and outside of the maneuvering area, and to expedite and maintain an orderly flow of air traffic (ICAO, 2016). Since ATC is facing challenges regarding higher traffic demands such as increased number of traffic movements (at least during the time of the work of this dissertation), improved fuel efficiency due to direct routes, and lower costs etc. while maintaining a high level of safety, the demands on the domain increases. For example, for a long time, the solution to handle the increasing number of traffic movements has been to divide the airspace into sectors. Moreover, when the traffic amount becomes too high for the ATCO to cope with in one sector, that sector is divided into smaller sectors. There is, however, a limit in how small these sectors can be in relation to ATCO's problem-solving efficiency. That limit has been reached in many places of the world. An option is then to limit the number of aircraft allowed to fly within a given sector, by means of queuing aircraft in a slot-system. In addition, there is the alternative of having free-route airspace, which is a specific volume of airspace where airspace users freely can plan a route between defined entry and exit points. However, this induces high complexity. At the same time, the ATC system needs to maintain high safety and increase productivity such as for the ATC system to accommodate more traffic without delays. The Swedish air navigation service provider, LFV (Air Navigation Services of Sweden), acknowledges the importance of maintaining a high level of safety when facing increased traffic demands:

> *"The future systems will need to enable the users to manage more traffic while maintaining or increasing the level of safety and offering a good working environment for the operators."* (LFV, 2016, p. 7)

Since there are certain ATC sites (not within every sector or at every airport) where ATCOs already are working with as much traffic as they can safely manage today, increased automation and, thus, new procedures must be implemented. This is to make it possible to introduce only positive outcomes with higher traffic demands. Although the system is very safe today, it is far from certain that the current ways of working are sustainable for coping with the future traffic demands. Consequently, the ATCO will need support in controlling the situation and to be able to make the right decisions in such increasingly complex work. Support can come from an automated system (but also from other ATCOs). Thus, human-automation teamwork is explored within the scope of this dissertation. Automation is, in this dissertation, considered as *a system that can help the operator with support, decision making, and execution of actions and tasks. A system which, in some cases and to some extent, knows what the operator is doing. A system the operator can see as a team member*. There are other definitions of automation (see Section 2.2.1). Thus, the scope for this dissertation extends to include the teamwork abilities of the automation.

Despite the many benefits of automation in control system domains, with one goal to aid human operators (with, for instance, decision support and planning support), many drawbacks have also been observed. As Mica R Endsley (2017) wrote: *"the more automation is added to a system and the more reliable and robust that automation is, the less likely that human operators overseeing the automation will be aware of critical information and able to take over manual control when needed."* (p. 8). If the human operator is not aware of what the automation is doing, it can lead to automation surprise (see Section 2.2.4), which in turn can lead to catastrophic consequences (Nunes & Laursen, 2004; National Transportation Safety Board, 2014; National Transportation Safety Committee, 2018). The effectiveness of the whole ATC system is, thereby, dependent on the development of successful human-automation teamwork approaches (Mica R Endsley, 2017).

Much can be learned from human-human teamwork. Working in teams of two or more ATCOs make teamwork a necessary attribute to establish safe procedures when encountering complex situations. However, with increasing automation, teamwork between humans is not sufficient to establish a sound cognitive system (see Section 1.1.2). The human operator needs also knowledge regarding what the automation can manage. Therefore, having automation work as a team member, the human operator needs to understand that team member to avoid automation surprise and to maintain safety.

1.1. Research objective

The overarching aim of this dissertation is to:

Explore human-human and human-automation teamwork within the cognitive system of ATC from a human factors design perspective.

To fulfil this aim, four studies (presented in four papers) have explored teamwork and automation in ATC from several angles. Table 1 provides an overview of the overall goals for each study. The first study (Paper I) explored human-human teamwork in current ATC environments in Sweden (en-route, approach, and tower control) to understand what kind of teamwork factors the ATCOs believe is of importance. The second study (Paper II) extended the first study by exploring human-human teamwork and human-automation teamwork in six different countries (Austria, Croatia, Denmark, Ireland, Portugal, and Sweden) to gain an understanding of how ATCOs perceive teamwork and automation in current and future ATC environments. The third study (Paper III) investigated ATCOs' work patterns in tower control to explore how to further develop human-automation teamwork. The fourth study (Paper IV) investigated ATCOs' work-as-done with a new automated ATC tool in en-route control and proposed a new automation-related concept that can be of use when designing automation to enhance the teamwork between the operator and the automation. Whereas Paper I and Paper II explored ATCOs' perceptions and beliefs about teamwork and automation, Paper III and Paper IV explored how the ATCOs are actually working with automation.

Table 1. Research goals for each study included in the dissertation.

Paper	Main goal
Paper I	Explore teamwork between ATCOs in four current ATC environments.
Paper II	Explore ATCOs' beliefs about current and future use of automation and teamwork.
Paper III	Explore the differences in ATCOs' work patterns in a conventional tower and a multiple remote tower.
Paper IV	Explore ATCOs' work-as-done with a new automated tool.

1.1.1. A human factors design approach

Human factors (and ergonomics) design takes into account humans' capabilities, limitations, and other human characteristics (Chapanis, 2002). Human factors design is highly important in the development of automation in high stakes environments to prevent errors (Mica R. Endsley, 2019), often caused due to bad designs which have not taken the operator's capabilities and limitations into account (Mica R. Endsley, 2019).

Human factors can be applied to the design of tools, systems, tasks, and environments for safe, comfortable, and effective use by the human. It is the design part of human factors which separates human factors from sciences such as psychology (Chapanis, 2002). Human factors design approaches can usually be found in multi-disciplinary research, such as cognitive science. Even though human factors is the overall design approach here, the work within the scope of this dissertation lies also within the areas of applied behavioural science, as well as human-computer interaction, and user experience.

Due to the differences between ATC environments (see Chapter 3) and to be able to explore several possibilities within human-automation teamwork with a human-centred point of view, an explorative design research practice within human factors has been used. Exploratory research activities can both inquire and produce new knowledge (Downton, 2003; Cross, 2007) through analyses and evaluations (Friedman, 2003). It can be closely linked to research methods where both quantitative and qualitative approaches may be appropriate (S. Roth, 1999). Consequently, the results from the work within the scope of this dissertation are founded on existing research, existing design solutions, and novel field studies.

1.1.2. A note on cognitive systems

A cognitive system is a system (potentially a socio-technical system where both humans and automation are involved in the work process, as in ATC) which can *"control its behaviour using information about itself and the situation"* (Hollnagel, 1998, p. 160). Thus, designing in regard to human factors refers (partly) to the design and development of systems that support the cognitive processes of users. A fundamental finding of cognitive science is that tools (and artefacts) shape cognition and collaboration. Therefore, if the researchers, designers, and the developers have an understanding of the cognitive system, there can be designs that can enhance and support cognition and collaboration in operational environments (Woods, 1998).

1.1.3. The knowledge contribution

In composing this dissertation, a comprehensive analysis was conducted of all four included studies with a focus on their contribution as a whole. As such, the work within the scope of this dissertation provides new insights drawn from these combined contributions, and is not only a summary of the four included studies.

The most important knowledge contribution is an increased understanding of the challenges in achieving human-automation teamwork in ATC working environments. The dissertation provides basic design concepts for overcoming these challenges. Empirical setups, data collections, and discussions with domain experts have led to the insights provided.

An overall conceptual design approach has been used, meaning that the findings of the work in this dissertation provide basic concepts for further design exploration regarding how automation might support and enhance teamwork. The results do not provide prototypes, sketches or artefacts. Instead, the basic concepts (two teamwork aspects) can be further explored by researchers and designers to generate more possibilities or solutions from a human-automation teamwork perspective (Hult, Irestig, & Lundberg, 2006). The results are also relevant for the ATC domain in general as it provides insights into the actual work of ATCOs. The results should also be of interest in other domains that are being similarly automated (e.g. maritime, train control, the car industry, etc.). In addition, the results can be used as a foundation for further design research regarding the development of human-automation teamwork models and how to apply models to different domains.

1.2. Scope and limitations

The work within the scope of this dissertation was funded by the Air Navigation Services of Sweden (LFV) and the Swedish Transport Administration (Trafikverket), through the project Amplify Teamwork with Automation. This has framed the research to some extent. For example, the focus and the results from this dissertation should benefit and be of interest specifically for the ATC domain. However, the rapid progresses in ATC research and development make the domain interesting with regard to human-automation teamwork and design of automation at large. Different levels of automation can exist, and level changes can occur dynamically in socio-technical systems such as ATC. This is something that can be found in several other domains as well such as train control, control rooms for nuclear power plants, and in the car industry, among other domains. Nevertheless, the above mentioned has shaped the scope, approach, and limitations of the dissertation:

- The ATC domain (including en-route, approach, and tower control) with operational ATCOs as participants has been the overarching case.
- Swedish ATC work has been in focus, but with one study (Paper II) involving European ATC work as well. Nevertheless, the results could be applicable to other countries facing the same challenges.
- The work within the scope of this dissertation is based on current developments within ATC. Due to the rapid developments within the domain, the research should continue regarding development and introduction of automation.
- Since it can be difficult for ATCOs to explain in detail what they are doing (their actions and decisions are mostly “autonomous” in that sense that it is a learned pattern evolved from many years of experience), both qualitative approaches, including case studies from real operations, simulator exercises during training, and interviews to capture the real-life situations, and a quantitative approach (with some minor qualitative sections) using an online questionnaire study was used.
- The work within this dissertation has considered one teamwork model; the Big Five model of effective teamwork (Salas, Sims, & Burke, 2005) to explore teamwork in the ATC domain (see Section 2.1 and Section 4.4). Other models might be suitable as well.

1.3. Structure of the dissertation

Chapter 1 introduces the problem, the aim and the developed research topic for this dissertation, and its limitations.

Chapter 2 presents the theoretical background behind teamwork and automation.

Chapter 3 describes the domain in focus for this dissertation, namely air traffic control.

Chapter 4 presents the methodological approaches and the industrial collaboration. The chapter ends with reflections regarding cancelled studies and lessons learned that has contributed to this dissertation.

Chapter 5 summarises the included papers. Each paper is presented with a short introduction, the used method, and conclusions.

Chapter 6 discusses the findings from the work. Based on the studies, two new teamwork aspects are being presented and discussed. The chapter ends with a discussion of future work.

Finally, **Chapter 7** concludes the results.

The full papers can be found at the end of the dissertation.

2. THEORETICAL BACKGROUND

When automation was first introduced in control rooms, it was seen as an either-or system. Either the automation was performing the actions or the human operator was. Analysis of automation initially regarded single decision steps and not entire chains of actions. However, in modern control rooms, many technical systems and automation work together and along with a human operator. No matter how capable the automation might be, many systems that include automation will still need to interact with human supervisory operators, who are responsible for guiding and overseeing the performance of the automation. In order to avoid misunderstandings between all of the team members and to create an efficient information flow, there is a need to design for a wider scene. Instead of single decision steps, the automation and the technical systems should be designed to support collaborative work and teamwork. It is required between the team members to maintain situation awareness.

2.1. Teamwork

There is a distinction between interaction, collaboration, and teamwork. Interaction is the communication between people or between humans and a technical system. The difference between teamwork and collaboration is that collaboration is a broader term that can involve individuals, groups, units, organizations, or combinations of any of them (Bedwell et al., 2012). Teamwork combines the efforts of all individual team members (humans or automation) to achieve a common goal. Consequently, teamwork is an example of collaboration.

A team is a set of two or more individuals, the team members, which can, for example, be humans, automation, or machines. The team members, the individuals, have different abilities, attitudes, characteristics, age, gender, and personality traits, i.e. team characteristics. The team members also have relationships with each other, such as friendship or professional roles. These relationships can affect the power and communication within the team (McGrath, 1964).

A team works within an environment, with goals and/or reasons. The team have one or several tasks which can vary in proportion and importance. The tasks can also vary between the team members. The results the team produce is referred to as team performance, i.e. how well the task is executed. In time, the team members will evolve, and the team will develop depending on the task, the team members' properties, and the team composition.

When talking about teams of humans, it is important to distinguish between teamwork and taskwork. Taskwork involves goals and task-specific requirements whereas teamwork involves interpersonal interactions and team member capabilities (Fisher, 2014). This dissertation focus on teamwork.

The benefits of teams are that they have the potential for greater adaptability, productivity, and creativity compared to a single individual. In addition, a team can provide more complex, innovative, and comprehensive solutions. (Gladstein, 1984; Sundstrom, De Meuse, & Futrell, 1990; Salas et al., 2005). Having an effective team with effective communication can help prevent inevitable mistakes from becoming consequential and harming customers, providers or stakeholders (Leonard, Graham, & Bonacum, 2004).

The character of teamwork is a complex phenomenon that can differ depending on the domain. Teamwork can be multidimensional and dynamic, including team members with their own cognition, behaviours, and attitudes. The team members perform a common task that results in coordinated actions (Wilson, Salas, Priest, & Andrews, 2007). For example, ATC is a dynamic environment where situations are unfolding rapidly and where fast decisions are needed by the team members. Several different kind of operator roles can be involved in the same team (Executive, Planner, sometimes shift lead, and the technical system) where all humans have their own cognition and behaviours. Hence, teamwork in ATC is multidimensional and dynamic, involving different kind of team members.

To enable comparison and generalisation, a well-known teamwork model was used within the scope of this dissertation for describing teamwork, the Big Five model (Salas et al., 2005). It is a framework that has been developed based on empirical studies and theoretical models of team performance.

According to Salas et al. (2005), the model contains factors which are necessary for successful teamwork. The five core factors in the model are *leadership*, *mutual performance monitoring*, *backup behaviour*, *adaptability*, and *team orientation*. Salas et al. (2005) also identified three coordinating mechanisms which they claim are needed to support the five main factors. These coordinating mechanisms are *shared mental models*, *mutual trust*, and *closed-loop communication*. The five main factors and the three coordinating mechanisms are listed in Table 2 together with the behavioural markers, which are descriptions of how each element may manifest itself during teamwork.

Table 2. The Big Five factors of teamwork and its coordinating mechanisms, explanations, and behavioural markers (Salas et al., 2005, pp. 560-561).[1]

Factors	Definition	Behavioural markers
Team leadership	The ability to direct and coordinate the activities of other team members, assess team performance, assign tasks, develop team knowledge, skills, and abilities, motivate team members, plan and organize, and establish a positive atmosphere.	• Facilitate team problem solving • Provide performance expectations and acceptable interaction patterns • Synchronize and combine individual team member contributions • Seek and evaluate information that affects team functioning • Clarify team member roles • Engage in preparatory meetings and feedback sessions with the team
Mutual performance monitoring	The ability to develop common understandings of the team environment and apply appropriate task strategies to accurately monitor teammate performance.	• Identify mistakes and lapses in other team members' actions • Provide feedback regarding team member actions to facilitate self-correction
Backup behaviour	The ability to anticipate other team members' needs through accurate knowledge about their responsibilities. This includes the ability to shift workload among members to achieve balance during high periods of workload or pressure.	• Recognition by potential backup providers that there is a workload distribution problem in their team • Shifting of work responsibilities to underutilized team members • Completion of the whole task or parts of tasks by other team members

[1]Permission has been acquired from all first authors for all tables and figures within this dissertation.

Adaptability	The ability to adjust strategies based on information gathered from the environment through the use of backup behaviour and reallocation of intrateam resources. Altering a course of action or team repertoire in response to changing conditions (internal or external).	• Identify cues that a change has occurred, assign meaning to that change, and develop a new plan to deal with the changes • Identify opportunities for improvement and innovation for habitual or routine practices • Remain vigilant to changes in the internal and external environment of the team
Team orientation	The propensity to take other's behaviour into account during group interaction and the belief in the importance of team goals over individual members' goals.	• Taking into account alternative solutions provided by teammates and appraising that input to determine what is most correct • Increased task involvement, information sharing, strategizing, and participatory goal setting
Shared mental models	An organizing knowledge structure of the relationships among the task the team is engaged in and how the team members will interact.	• Anticipating and predicting each other's needs. Identify changes in the team, task, or teammates and implicitly adjusting strategies as needed
Mutual trust	The shared belief that team members will perform their roles and protect the interests of their teammates.	• Information sharing • Willingness to admit mistakes and accept feedback
Closed-loop communication	The exchange of information between a sender and a receiver irrespective of the medium.	• Following up with team members to ensure message was received • Acknowledging that a message was received • Clarifying with the sender of the message that the message received is the same as the intended message

Figure 1 illustrates the interrelationships between the factors in the Big Five model and are further described below.

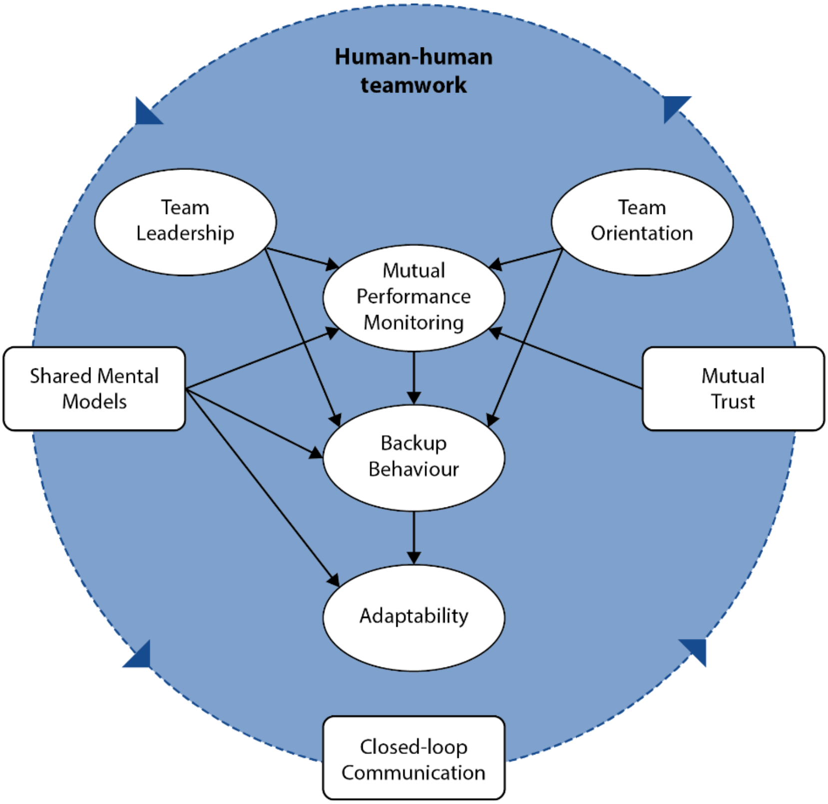

Figure 1. The interrelationships between the teamwork factors in the Big Five model. Illustration adapted from Salas et al. (2005, p. 571)[4].

Salas et al. (2005, pp. 574-586) proposed how the factors affect team effectiveness (illustrated in Figure 1):

- *Team leadership* influences team effectiveness through reinforcements of performance expectations such as *mutual performance monitoring* and *backup behaviour*.
- Through effective *backup behaviour*, *mutual performance monitoring* affects team effectiveness.
- *Mutual performance monitoring* occurs only in teams having trust and acceptable *shared mental models*.

- *Backup behaviour* affects team performance by ensuring that all the team tasks are fulfilled.
- *Backup behaviour* is mediated by the ability to adapt to internal and external changes.
- *Backup behaviour* requires adequate *mutual performance monitoring* and *shared mental models*.
- Team effectiveness is directly affected by the team's *adaptability*.
- *Adaptability* requires adequate *shared mental models*, *mutual performance monitoring,* and *backup behaviour*.
- The team effectiveness is through *team orientation* affected by the teams' engagement in *mutual performance monitoring*.
- The team effectiveness is through *team orientation* affected by the acceptance of feedback of assistance through *backup behaviour*.

According to Salas et al. (2005), the Big Five model contains factors which are necessary for effective teamwork, regardless of the type of team and domain. However, it is necessary to investigate how it manifests in each domain (for example en-route, approach, and tower in ATC) since circumstances such as team tasks and the environment can and will affect how the factors appear in a team.

As a comparison to the Big Five model, McGrath (1964) described teamwork as a cycle of input – process – output. The output is the results the team produces, which in time alters the input conditions for the next cycle. However, instead of focusing on input and output, the Big Five model can be used to uncover the "black box" of the actual teamwork processes (what the team members are doing, how they communicate, and how the different teamwork factors manifest) and not only the results of it. The Big Five model aims to cover central aspects of teamwork. In addition, it has been applied to several domains. For example, the Big Five model has been used in a study of army peace-keeping teams (Duel, 2010) and in a learning environment (Kay, Maisonneuve, Yacef, & Reimann, 2006). It has also been used in interviews with fighter pilots about their experiences of teamwork (Ohlander, Alfredson, Riveiro, & Falkman, 2016).

A slightly different teamwork model, applied in ATC, is the Taskwork and Teamwork strategies in Emergencies in Air traffic Management (T^{2}EAM) model (Malakis, Kontogiannis, & Kirwan, 2010). It includes team orientation, coordination, information exchange (communication), change management, and error management (Table 3). In a study by Malakis et al. (2010), ATC students and operators were observed in simulated emergencies and abnormalities to validate their model. In the study, the participants did not have a formal leader. Instead, they relied on the assertiveness of the operators, something which can be found in Crew Resource Management (CRM) (Cooper, White, & Lauber, 1979). In addition, error management is something which CRM training is trying to cover since the aim of CRM training is to manage errors, not to totally eliminate human errors and to assure safety by increased teamwork per se. Hence, when educating teams in high stakes environments, CRM training can be one tool to increase the safety culture.

Table 3. Teamwork strategies and elements of T^{2}EAM (Malakis et al., 2010, p. 630)[4].

Teamwork strategies	Elements
Team orientation	Shared situation understanding Communication of intent
Team coordination	Managing dependencies and adopting assertive stance Avoiding information garbling and interruptions
Information exchange (Communication)	Unsolicited dissemination of information Updates on situation status and its management
Error management	Error detection by team members Feedback for error correction
Task distribution (Change management)	Problem detection in task distribution Changes in task allocation

The T^{2}EAM model is not as detailed as the Big Five model but includes error management which the Big Five model does not have as a category. However, the Big Five model has *mutual performance monitoring* which can assist in detecting errors. Both of these models cover communication, adaptability, shared understanding, information sharing, and feedback. There are also models covering teamwork breakdowns and team cognition (Wilson et al., 2007). This model discusses, among other things, how *backup behaviour*, *mutual performance monitoring*, and *adaptability* contribute to shared cognition. Even though the work in their study focused at the battlefield, breakdowns can occur in any team. Multiple studies have also explored how to improve teamwork. Leonard et al. (2004) identified communication and adaptability to cultural changes as keys to prevent mistakes in patient care. In addition, there is research regarding measuring teamwork. For example, Brock, McAliney, Ma, and Sen (2017) identified that managers' view on teamwork did not match the predicted team success. The team required good communication but added also that effective listening was a key contributor to the success of the team. They also relied upon discussions, flexibility, and trust, and not only effective conflict resolution techniques. The instruments they used did not include the team members' strengths and weaknesses, which also can be of importance when measuring teamwork.

Situation awareness (Mica R. Endsley, 1995) is important for teamwork. However, the models above do not focus on shared situation awareness as a team being effective through the sum of the team members' situation awareness. Instead, team members *"experience a situation in different ways (as defined by their own personal experience, goals, roles, training, knowledge, and skills and so on) and, therefore, their awareness is compatible rather than shared."* (Salmon, Stanton, & Jenkins, 2017, p. 208). This can be applied in ATC since the ATCOs are getting the same training, have similar information about the traffic situation but does not experience the work situations in similar ways due to different roles and skills.

2.2. Automation

Although the Air Traffic Management (ATM) system (ATM and ATC related definitions can be found in Chapter 3) is very safe today, it is far from certain that the current ways of working are sustainable for the increasing traffic demands. Therefore, since the ATCOs in certain ATC environments are already working with as many traffic movements as they can safely manage, increased use of automation (along with new procedures) is implemented to make it possible to maintain high safety while at the same time increase efficiency.

Automation is a complex phenomenon, and implementing automation will change the very nature of the operator tasks (Woods, 1996; M. Scerbo, 2008) (this realisation is also illustrated in Paper IV). There is a lot of research regarding automation, the effects of automation in aviation, and their impact on the role of ATCOs (Kelly & Goillau, 1996; Cox & Kirwan, 1999; Mica R Endsley, 2017; Strauch, 2017). Due to the fact that a single mistake in a control room (such as in ATC) or in a cockpit can lead to catastrophic consequences and cost lives and money, a substantial amount of public and private money has been invested in psychological and behavioural research regarding automation effects. For example, it was the focus of the "Programme for Harmonised Air Traffic Management Research in Eurocontrol (PHARE)" (Eurocontrol, 1993) and of the European Commission's project "Role of the Human in the Evolution of ATM Systems (RHEA)" (Nijhuis et al., 1999). In addition, studies regarding automation have focused at how to reduce workload (Earl L Wiener, 1985; Edwards, Homola, Mercer, & Claudatos, 2017), decrease vigilance (Earl L. Wiener & Curry, 1980; Earl L Wiener, 1987), and to decrease confusion about responsibilities between automation and operator (Farrell, 1987) to name a few. The research around automation has also focused on trust (Muir, 1994; Bonini, Jackson, & McDonald, 2001; Eurocontrol, 2003; de Visser et al., 2016), conformance (C. Westin, Borst, & Hilburn, 2016), complacency (Parasuraman, Molloy, & Singh, 1993; Parasuraman & Manzey, 2010), and transparency (Christoffersen & Woods, 2002; Chen, Barnes, Wright, Stowers, & Lakhmani, 2017; C. A. Westin, Palmerius, Johansson, & Lundberg, 2019). In addition, much research has been conducted regarding how to increase situation awareness (Mica R. Endsley & Kaber, 1999; Jipp & Ackerman, 2016) how to avoid the out-of-the-loop problem (David B. Kaber & Endsley, 1997; Mica R. Endsley, 2018), and how to decrease automation surprise (N. Sarter et al., 1997; De Boer & Dekker, 2017).

2.2.1. History and definition of automation

It seems that the word *automation* entered the spoken language quite recently in 1946 with a Vice President at Ford Motor Company describing the latest machinery installed on the assembly line with the words *"Give us some more of that automatic business". "Some more of that-that automation"* (Carr, 2014, p. 34). However, the mechanics of automation has been around for a long time. Between 300 BC and 1220 AD, the Greeks and Arabs used a float regulator for a water clock to keep track of time. In addition, prime movers, steam engines, and pressure regulators are also examples of early automation. The Industrial Revolution brought the feedback control systems, and later on, the relay logic was introduced. Automation appeared in the central control rooms, which has been common since the 1920s where it was mainly an on and off process (Bennett, 1993). Over the years, the automation has developed and higher levels of automation (see Section 2.2.3 and Chapter 3) are being introduced in various high stakes domains, such as in nuclear power plants, the car industry, in health-care, and in ATC. The car industry has come a long way regarding technical development with speed control, lane-keeping assistance, navigation systems, and so on. However, this is a path that the aviation industry went down decades ago. The history of automation in aviation begins in 1914 when Lawrence Sperry flew a Curtiss C-2 with the world's first automatic pilot, the so-called "gyroscopic stabilizer apparatus", invented by Sperry and his father. Twenty years later, the gyroscopic autopilot reached the commercial flight. In 1933, Wiley Post completed the first solo flight around the world with assistance by the Sperry's autopilot he called *"Mechanical Mike"*. The New York Times wrote: *"Revelation of the new art of flying"* and *"Commercial flying in the future will be automatic"* (Mohler, 1971; Carr, 2014).

The introduction of the gyroscopic autopilot was the starting point of the expansion of the aviation's role in transport, but also in warfare. In 1930, automatic steering and automatic stabilisation progressed very rapidly. By letting the machine doing much of the exhausting work with sticks and pedals etc. it freed the pilots' hands, eyes, and also minds for other subtler tasks. The pilots now had instruments to consult; they could solve more problems and think more analytically. With the new technology, they could also fly higher and longer, and in bad weather, which would before had kept them grounded. Additionally, the aircraft also changed and became faster and more complicated.

With World War II came another wave of innovation in aviation and in 1947, the U.S. Army Forces conducted a complete flight with autopilot, including take-off from Newfoundland to landing in Oxfordshire. The pilot sat with his hands in his knees during the entire flight. His only role was to start up the engines and park the plane after landing. An anonymous writer for the British aviation magazine “Flight” concluded that, even though it seems that machines can do the pilots’ jobs, the pilots are still necessary. *“if only to watch the various clocks and indicators and see that everything is going satisfactorily, and to correct any discrepancy if it happened to arise; he should also be able to take over manual control if necessary.”* (Anonymous, 1947, p. 418).

In 1988, another major step within aviation was taken. The Airbus A320 was introduced with the “glass cockpit”. Cathode ray tubes screens were developed ten years earlier, but what separated the A320 from the previous aircraft was the fly-by-wire system. Before this system, commercial planes operated mechanically with a direct link between the pilot and the aircraft. The fly-by-wire system disengaged this tactical link and was replaced with a digital computer that converts the pilot’s commands to the aircraft’s response. This also led to a redesign of cockpit controls with many flat screens. As Don Harris wrote, the flight deck can be seen as *“one huge flying computer interface”* (Harris, 2016, p. 221). The computer did not only change the character of the flight, the role of the pilot from controlling the aircraft to only monitoring computers, it also changed the character of automation (Carr, 2014). The pilot does not have manual control in the sense as they are actually controlling the aircraft. Commercial pilot’s role is to send digital signals, which can actually be overridden by the software in extreme cases. The computer gets the final word in modern aircraft. However, this does not mean that important skills are not involved anymore, more that the skills have changed.

Over the years, the term automation has developed and new perspectives of it have been introduced. Parasuraman et al. (2000) defined automation as *“a device or system that accomplishes (partially or fully) a function that was previously, or conceivably could be, carried out (partially or fully) by a human operator”* (p. 287). Another definition was proposed by Hancock (2017) as *“automated systems are those designed to accomplish a specific set* *of largely deterministic steps, most often in a repeating pattern, in order to achieve one of an envisaged and limited set of pre-defined outcomes"* (p. 284).

Innovations have led to advanced computers, and the automation has reached beyond the work of the hand, and into the work of the mind. Highly modern automation is nowadays introduced in control systems to aid the human operator in decision making and with execution of actions. However, advanced automation might be introduced in systems that already has older versions or lower levels of automation. Therefore, when implementing automation, it must be compatible with previous technical systems that have various degrees of advanced functions and life cycles, as well as with the human operator.

2.2.2. Automation vs autonomy

In addition to automation, research within autonomy has also been conducted over the past 40 years, especially in the field of human-automation interaction. However, even though there has been some research regarding autonomy, there are still few examples of it in current operations. The goal of autonomy is to achieve functions independently, with little or no human intervention (Krogmann, 1999). It is supposed to function and handle uncertainties well during extended periods of time. Hancock (2017) defined autonomous systems such as they are *"generative and learn, evolve and permanently change their functional capacities as a result of the input of operational and contextual information. Their actions necessarily become more indeterminate across time"* (p. 248).

Autonomy can be described using five stages. The first stage is monitoring by recognising the actual state of the environment and compare it with the desired state. The second stage is to diagnose by analysing the deviations of the actual and desired state. The third stage is to plan by thinking about actions to modify the state of the world. The fourth stage is to select a plan by deciding the necessary actions to reach the desired state. The last stage is to execute the plan by taking the necessary actions to change the state of the world (Krogmann, 1999, p. 4). In addition, autonomy is supposed to have the ability to compensate for system failures.

Autonomy uses learning algorithms to better adapt to unanticipated and dynamic situations, compared to previous generations of automation that normally use logic-based programming. Autonomy can be seen as an increased level of automation. In other words, automation and autonomy represent different stages of the computational evolution (Hancock, 2017). However, simple automation will continue to assist humans while others will evolve into autonomy. With the rapid development and innovative research, the change from automation to autonomy is approaching rapidly. Even though autonomy sounds promising with performing actions alone with little or even no intervention from humans, the development is not there yet. The likelihood is that many systems will continue at a level of semi-autonomy for many years to come (Mica R Endsley, 2017).

For this dissertation, the concepts of automation and autonomy will be treated as synonymously since it is focused on the exploration of how human operators interact with automation in general in ATC and human-automation teamwork.

The following sections elaborate on particular aspects of automation that were central in the studies of this dissertation. In particular, levels of automation, automation surprise, ironies of automation, situation awareness, and teamwork with automation.

2.2.3. Levels of automation

Taking a step back to early work on human-automation interaction, levels of automation was an early notion that still is highly influential. Ground-breaking work in the field of creating the taxonomy levels of automation was performed by Tomas B. Sheridan, Verplank, and Brooks (1978), who created a hierarchy of levels of automation for underwater teleoperations. Their approach to levels of automation is one of the oldest taxonomies and many researchers have based their models and ideas on this one. In this model, the machine is still present in all of the steps as the executor of the action. Six functions were identified that could be carried out both by the human operator or by the automation during undersea teleoperation control; gets, selects, starts, requests, approves, and tells. With these functions, they developed a 10 level model of automation which has served as a foundation over the years for research within automation and collaboration between humans and machines. To be noted, this level of automation taxonomy regards one single decision step. The levels are:

1. Human does the whole job up to the point of turning it over to the computer to implement.
2. Computer helps by determining the options.
3. Computer helps determine options and suggests one, which human need not follow.
4. Computer selects action and human may or may not do it.
5. Computer selects action and implements it if human approves.
6. Computer selects action, informs human in plenty of time to stop it.
7. Computer does the whole job and necessarily tells human what it did.
8. Computer does the whole job and tells human what it did only of human explicitly ask.
9. Computer does the whole job and tells human what it did and it, the computer, decides he should be told.
10. Computer does the whole job if it decides it should be done, and if so tells human, if it decides he should be told. (Tomas B. Sheridan et al., 1978, pp. 8.17-19).

Compared to Tomas B. Sheridan et al. (1978), Mica R. Endsley (1987) presented a more compact model consisted of four automation levels, exemplified by an advanced cockpit. The four functions can all be carried out by both humans and machines. These functions consisted of; suggest, agrees, act, and veto. This model does not consist of a fully manual level.

Up to this point in time, automation has been seen as an either-or-system: the automation is in control or the operator is in control. But there have been discussions from Earl L. Wiener and Curry (1980) and C. E. Billings (1991) about the fact that automation can be implemented at various levels and stages of the process. Parasuraman et al. (2000) emphasized different aspects of control by proposing that automation could be applied to four different human information processing functions: information acquisition, information analysis, decision selection, and action implementation. They claimed that different levels of automation, fully low to fully high, can be applied to all four stages. In addition, any of these levels of automation should be evaluated by looking at how it is associated with the consequences of human performance. For this, they developed four primary evaluative criteria for automation in design: workload, situation awareness, complacency, and skill degradation and two secondary evaluative criteria: automation reliability and costs of decision/action-outcome. The model from Parasuraman et al. (2000) refers mainly to automation that makes suggestions, decisions, and executes actions. However, automation can also sense and process information to detect interesting situations (Miller & Parasuraman, 2003).

In addition to the mentioned models, several more models and taxonomies have been developed. Lorenz, Di Nocera, Röttger, and Parasuraman (2001) proposed a three-step taxonomy that consisted of a baseline, the automation support, and an automation support failure level. Proud, Hart, and Mrozinski (2003) had eight steps in their model for determining the appropriate level of automation for each function of a system. Another taxonomy has been proposed with 11 steps (Fereidunian, Lehtonen, Lesani, Lucas, & Nordman, 2007; Fereidunian, Lucas, Lesani, Lehtonen, & Nordman, 2007) which are very similar to the one Tomas B. Sheridan et al. (1978) proposed, except for one more level; level 0 that is fully manual by the human. Furthermore, the levels of automation taxonomy has been widely used in research and development in ATC. For example, SESAR (2013) even proposed a new taxonomy of levels of automation, based on the four-stage model of human information processing proposed by Parasuraman et al. (2000). The taxonomy from SESAR is, however, more detailed and has 9 levels of automation and explains each level from information acquisition to action implementation.

David B Kaber (2018) argued that to be able to discuss human-automation interaction, we need to have a more descriptive definition of levels of automation, which could lead to a more accurate and a precise prediction of human automated systems performance. It should start with “what” the automation and humans will do and “how” they will do it. Further, J. D. Lee (2018) argues that multiple perspectives such as “what is connected” should be considered rather than only “who does what”. Analysing what is connected could identify issues that emerge from several elements interacting (one automation might have several automated elements which creates an automated system). Issues that would go undetected if there only was a focus on individual elements of the automation.

2.2.4. Ironies of automation

While many celebrate the arrival of automation, seeing it as a symbol for progress and prosperity, others, and especially the operators, are worried that the machines and automation will steal their jobs or make them lose control over the situation. Even though automation can have many benefits, it also creates new types of errors that must be addressed (Bainbridge, 1983; Strauch, 2017).

When automation was first introduced in complex environments in the early 1900s, the assumption was that workload and performance were inversely correlated. It was believed that by easing the mind of the operator, the person would be smarter and better at the job. However, the reality is not that simple. The relationship between humans and computers/machines has become very complex, especially when it comes to errors and blame. Having automation rarely plays out as expected. As Nijhuis et al. (1999, p. 36) wrote: *"automation frequently changes the very nature of the task"*. Sometimes humans do not even know if the technology is there to help or to control. Humans are the end-users or the operators behind the panels. However, sometimes the humans are not sure if they are the ones in control.

For instance, automation can cause deskilling (decrease in learning and loss of operational skills) and hinder the operator from getting deeper skills. Since the automation does all the computational work, the analysis, and the predictions, it also prevents the operator from deep learning. In addition, automation can cause out-of-the-loop problems (David B. Kaber & Endsley, 1997), meaning that the operator is removed from the control loop (e.g. no longer having control over and giving clearances to aircraft in the airspace) due to allocation of functions to an automation being in direct control instead. Thereby, the operator's interactions with the system become limited. Consequently, the operator's awareness of system states may be reduced.

There is also a distinction between physical and cognitive aspects of control that can be related to the out-of-the-loop problem (Louw, Kountouriotis, Carsten, & Merat, 2015). The loss of physical control generally refers to taking the hands away from the panels while loss of cognitive control generally refers to taking attention away from the main task. The work within the scope of this dissertation mainly focus on cognitive control.

Moreover, other risks with automation are automation bias (using the automation as a replacement for vigilant information and process seeking) and complacency (operator's over-reliance in automation). Both originates from human's inability, or limitations, to pay attention. If humans are not interacting with the environment, they easily lose attention. Automation bias can especially be a risk for operators using decision support tools (like ATC). In the end, it might lead to errors and even disasters.

Having different levels of automation in operation together with a human operator can cause automation surprise (N. Sarter et al., 1997; De Boer & Dekker, 2017), meaning that the automation fails in executing or performing its actions which are unexpected for the human operator. This can leave the human operator in confusion and risks. One reason for automation surprise is mode errors, meaning that the human operator forgets or is unaware of which mode or state the automation is in (N. Sarter & Woods, 1995). Moreover, operators can misunderstand information provided by automation and technology (Bonini et al., 2001). Aviation has suffered from several incidents due to automation surprises such as undetected behaviour of the autopilot or faulty mental models of the autopilot by the pilots (De Boer & Dekker, 2017; Trippe & Mauro, 2017). More recently, the Lion Air and Ethiopian Airlines crashes of the Boeing 737-Max8 aircraft might be blamed on the lack of the human factors research area in the development of the aircraft, and thus, resulting in automation surprise and loss of situation awareness (Mica R. Endsley, 2019). To maintain awareness of a situation, to avoid automation complacency and automation bias, the operator needs feedback from the automation. The operator needs to know when or if something is wrong, not when it is already too late, but sooner. By isolating the operator from feedback from the automation, it becomes harder to stay alert and engaged in the task and, thereby, the operator disconnects even more (Carr, 2014).

There is a shift between manual control to a monitoring role for the operators when introducing more automation. Therefore, research is needed regarding operator work with automation for the operator to maintain situation awareness while at the same time have awareness of the automation. Consequently, the research within the scope of this dissertation includes aspects of situation awareness.

2.3. Situation awareness and mode awareness

The ability to stay in the loop of control, to maintain awareness about the situation, and to keep track of dynamic events, can be described with the term Situation Awareness (SA) (Mica R. Endsley, 1995, 1996; Neville A. Stanton, Salmon, Walker, & Jenkins, 2010; Carsten & Vanderhaegen, 2015; Mica R. Endsley, 2015; Lundberg, 2015; N. A. Stanton, Salmon, Walker, Salas, & Hancock, 2017). SA is about having knowledge of a situation to make decisions regarding the near future (Mica R. Endsley, 1995). Basic SA theory has three levels. The first level is the SA state, the operator's perception about the status, characteristics, and dynamics of relevant elements in the operator's environment. The second level is the SA process, meaning what information the operator uses to comprehend the situation and to maintain the knowledge about it. The third level is a projection of near-future actions which is achieved through the other two levels. The three levels in the model by Mica R. Endsley (1995) can be compared with an input – process – output model, where information is going into the system (the human mind), being processed, and generates a result (an action, a decision, or increased knowledge).

SA can be seen as a top-down process, driven by pre-understanding. It can also be seen as a bottom-up process, driven by new information. The search for information generates details about the (assumed) situation; it generates questions about the current understanding and generates new understandings. The activity of generating new understandings is sometimes referred to as framing (Gary Klein, Pliske, Crandall, & Woods, 2005; Malakis & Kontogiannis, 2013; Lundberg, 2015).

In ATC, ATCOs work within the same system and share the same overall goals (to prevent collision and expedite and maintain an orderly flow of air traffic). However, even though the ATCOs share the same goals, the ATCOs may not have the same specific tasks. Therefore, the ATCOs may also have different SA. However, the ATCOs may share situational information and, thus, have a shared understanding of the situation. Further, ATCOs are often working in teams of two or more ATCOs. Therefore, SA within teams is not only the sum of individual SA but a cooperative process based on mutually shared goals (Garbis & Artman, 2004) (and *shared mental model (see Section 2.1)*). Working in teams with the same goals, the ATCOs share and distribute their SA between each other to form a common awareness about the situation.

Many attempts have been made to explain SA in teams and how the awareness about the situation is distributed amongst team members. For instance, team members can have SA for their own requirements, i.e. team SA that can be described as *"the degree to which every team member possess the SA required for his/her responsibilities"* (Mica R. Endsley, 1995, p. 39). Another definition of team SA is *"the active construction of a model of a situation partly shared and partly distributed between two or more agents, from which one can anticipate important future states in the future"*, proposed by Artman and Garbis (1998a, p. 2). Their idea was to emphasize the explanatory and distributed nature of team SA. In addition, team SA does not only have to involve human agents, but also the extensive use of various artefacts or tools (e.g. computer screens and displays) (Artman, 2000; Garbis & Artman, 2004) such as within ATC.

Team SA is related to shared SA which refers to shared requirements, purposes, and understanding within the team (van Westrenen & Praetorius, 2014). Shared SA can be defined as *"the degree to which the team members possess the same SA on shared SA requirements"* (Mica R. Endsley & Jones, 1997, p. 38). However, there is a difference between shared and distributed SA as well where distributed SA refers to different, and possibly compatible, requirements and purposes within the team (Neville A Stanton et al., 2006). Meta-SA is the understanding of the other team member's SA and how well it matches with the one's own SA (van Westrenen & Praetorius, 2014).

Once there is mutual SA in the team, it is equally important to maintain the SA. Achieving SA is not a static state; it must be maintained as the dynamic situations unfold. Each situation is different from the previous one and unfolds rapidly and in real-time, especially in control room domains such as ATC. Thus, information to maintain SA needs to be communicated within the team. Much research has been conducted regarding communication, team performance, and how to avoid communication failure in safety-critical environments (Artman & Garbis, 1998b; Lingard et al., 2004; Salas, Wilson, Murphy, King, & Salisbury, 2008; Malakis et al., 2010). However, communication is not a simple transfer of information from one agent to another. The receiver of the message needs to actively interpret and understand the meaning of the information, something which does not happen automatically (Artman & Garbis, 1998b). In addition, research has been conducted regarding communication in ATC, communication failure with pilots, and phraseology (Rognin & Blanquart, 2001; Prinzo, Hendrix, & Hendrix, 2007; Rakas & Yang, 2007; Malakis et al., 2010). Research on communication has not only concerned human team members, but also teams of humans and automation (Balch & Arkin, 1994; Pereira, Pimentel, Chaimowicz, & Campos, 2002; Breazeal, Kidd, Thomaz, Hoffman, & Berlin, 2005).

SA can be related to the concept of mental models (Craik, 1967) that are representations of the surrounding environment and situation. SA can also be related to the concept of device models (Kieras & Bovair, 1984), which concerns how to operate with unfamiliar equipment. Mental models and device models can be used to reach SA and can be pre-understandings from training and experiences.

In ATC, the ATCO must maintain an up-to-date assessment of the dynamic situations regarding traffic, weather, and other relevant elements. The traffic situation in ATC is central to SA. Adding automation to such system adds the need for the human operator to monitor and control the automation, while also still monitoring and controlling the traffic. Mental models and device models are used to plan and predict the future but are also used to understand the automation.

For almost all automation, humans need to know what the automation is doing and why. Mode awareness (N. Sarter & Woods, 1995) is important in high stakes environments such as aviation or the car industry. Even though aircraft around the world are highly automated and autopilot is used, there are almost always two pilots in the cockpit for commercial airlines. This is because of safety reasons and to be able to detect errors, misunderstandings and to double-check the information. The pilots have knowledge and education about the autopilot and should know how it works and why it acts in certain ways. Therefore, if something happens, they can take over and steer the aircraft and know in which mode the aircraft is. In addition, automation may function in various modes, and switch between modes, and with various performance characteristics. Some advanced automation may alter modes automatically without human interference (N. Sarter & Woods, 1995). Thus, the human operator must have mode awareness that helps *"the ability of a supervisor to track and to anticipate the behaviour of automated systems"* (N. Sarter & Woods, 1995, p. 7).

2.4. Human-automation teamwork

Teams consisting not only of humans but also of technical systems has been considered by many researchers throughout the years (Bowers, Oser, Salas, & Cannon-Bowers, 1996; N. B. Sarter, 2001; Christoffersen & Woods, 2002; Glen Klein, Woods, Bradshaw, Hoffman, & Feltovich, 2004; D. Norman, 2017). A human-automation team can be described as *"the dynamic, interdependent coupling between one or more human operators and one or more automated systems requiring collaboration and coordination to achieve successful task completion"* (Cuevas, Fiore, Caidwell, & Strater, 2007, p. B64). For example in the cockpit, the pilot often transfers the control to the autopilot during normal flight operations, transforming the automation into a member of the flight crew. Interacting with such systems can be compared with interacting with a team member. It is suggested that the automated systems need to be smart so they can understand the other team members' conditions, their intentions, the current situation, and, hence, behave like a team member (Inagaki, 2008).

The work within the scope of this dissertation uses the view on human-automation teamwork as Wijngaards, Kempen, Smit, and Nieuwenhuis (2005) do: *"intelligent systems such as agents and robots can also be team members, equivalent in status to humans [since] agents (whether software entities on a network or robots) may also take the initiative and give orders to human (and other agent) team members"* (p. 35).

Automation may not only change the very nature of the operator's work, but it may also change how operators are working and interacting with other people and machines. In line with automation reducing workload for the human operator by eliminating or assisting in some tasks, it can also introduce new tasks such as monitoring the automation. This can, in turn, change the distribution of work between the team members. Hence, it might also create new demands on teamwork. For example, new requirements for communication for the team members might be necessary to maintain understanding of the situation and about the other team members' intentions and actions (such as *mutual performance monitoring*) (Hutchins, 1995; Gary Klein, Feltovich, Bradshaw, & Woods, 2005).

2.4.1. Human-automation teamwork design

As Mica R. Endsley (2019) wrote: *"bad design encourages accidents; good design prevents accidents"* (p. 1). Even though the aim of automation is to aid and assist, to even make the work more efficient and reduce human errors, automation also creates new types of errors that needs to be considered and addressed. Many researchers have claimed that additional training and education is the (only) possibility. However, the problems arising with automation must at a first stage be addressed through careful system design. Today, part of the problem regarding the fact that automation surprise still exists is that the developers of new systems do not take into account human factors and the operators that are working with the finished design (D. A. Norman, 1990; N. Sarter et al., 1997; Baxter, Rooksby, Wang, & Khajeh-Hosseini, 2012; Mica R. Endsley, 2019), or the operators' acceptance of automation (Hilburn & Borst, 2014; Bekier & Molesworth, 2017). To be able to handle automation surprise and ironies of automation, there is a need to develop procedures for the operator to anticipate rather than respond to system technological changes. These procedures need to be developed both for the operator but also for the developers and designers (Strauch, 2017; Mica R. Endsley, 2019). With more automation, the operator still needs to be in the loop to avoid loss of control or loss of situation awareness (David B. Kaber & Endsley, 1997; Strybel et al., 2016) but at the same time avoid automation complacency, which is something the developers need to consider. In short, understanding transitions and variations are at least as important as understanding tasks at specific levels of human-automation interaction.

Many researchers have tried to identify general characteristics of desired human-automation interaction (Parasuraman & Riley, 1997; Glen Klein et al., 2004; J. D. Lee & See, 2004; Gary Klein, Feltovich, et al., 2005). For example, P. U. Lee (2005) explored the collaboration between ATCOs and pilots and how it might change with future support tools. They found that the ATCO need to stay in the loop of control, that the automation should be transparent, and while some tasks the ATCO is now performing can be delegated to automation while others cannot. In relation to the work within the scope of this dissertation, it is argued that having the operator in the loop of control is of high importance in ATC where the operator still has the legal responsibility when working with automation, even though some tasks are delegated to an automation.

However, the question of what functions or tasks that should be automatized has no simple answer. Lists of function allocation, or "Men Are Better At – Machines Are Better At" lists, and how these can be used in human-automation teamwork (E. M. Roth, Sushereba, Militello, Diiulio, & Ernst, 2019) have been provided by several researchers (Fitts, 1951; Chapanis, 1965; Thomas B Sheridan, 1987). However, such lists have a presumption that humans and machines/automation have fixed strengths and weaknesses. They imply a quantitative division of work between the human and the automation, meaning that the automation does a certain amount of tasks and the operator does a certain amount of tasks (S. Dekker & Woods, 2002). This division of work contributes to loss of situation awareness, out-of-the-loop, and ironies of automation, especially during automation failure. However, there are challenges regarding the degree of controlling and authority between the human operator and the automation. An even more qualitative approach of how to make the human and the automation get along is more important and how to make automation into a team player (Christoffersen & Woods, 2002; Glen Klein et al., 2004).

Attempts have also been made to create design guidelines which address human-system teamwork, collaboration, and task allocation (C. E. Billings, 1991; Donald A. Norman, 1993; Hilburn & Flynn, 2001; Glen Klein et al., 2004; O'Hara & Higgins, 2010; Oxstrand et al., 2013; D. Norman, 2017). However, the envisioned world problem (S. W. A. Dekker, 1996; S. Dekker & Woods, 1999) is difficult to design for since introducing automation might create fundamental reverberations and change the work of the operator.

2.4.2. User acceptance

Increased use of automation within any system or domain is dependent on user acceptance of the automation (Hilburn & Flynn, 2001; Bekier, 2013). Within the ATM industry, it is believed that new automation can be met with great resistance from the ATCOs (Hilburn & Flynn, 2001; Bekier, 2013). Various factors affect whether automation is accepted and used, for instance, age, experience, and job satisfaction (Parasuraman, Duley, & Smoker, 1998; Nijhuis et al., 1999; Eurocontrol, 2000; Thompson & Bailey, 2000; Eurocontrol, 2004; J. D. Lee & See, 2004; Bekier, 2013; Mirchi et al., 2015). It appears that for many ATCOs it is difficult to accept new automation concepts, and even more so if they cannot see the benefits of it (Eurocontrol, 2004). Previous research has shown that ATCOs approve of automated tools that assist them in organizing materials needed to be decided on, but dislike tools which take over the authority to make decisions (Bekier, 2013). In a study by Bonini et al. (2001), operators wanted the technology to remain as a support, and that it would not take over control and decision making, i.e. the aspects that the controllers enjoyed the most with their work. The willingness to accept automation appears to be task-dependent and also dependent on the purpose or intent of the automation (Bekier, Molesworth, & Williamson, 2011). Thus, operators might accept advisory automation as long as they remain in the control of making decisions (Hilburn, 2000). In addition, trust is an important element for the system to work accurately (Bonini et al., 2001).

The operators from the study conducted by Hilburn (2000) reported that they believed trust regarding the system refers to confidence in the system and to know that the information provided, from both system and colleagues, is correct. There is extensive research regarding trust with automation. Therefore, the work within the scope of this dissertation refers mainly to the already existing research regarding trust. Paper I and Paper II refer to trust as part of the Big Five model.

In summary, to design automation to become a trusted team member that the human operator wants to work with, there is a need to understand the nature of operator’s work and practice (and the domain) for the designers and developers of the automation to design automation to support the work of the operator. It is not sufficient to add more automation or replace the human operator with automation. It is about enabling teamwork. Therefore, the studies within the scope of this dissertation have explored the topic of human-automation teamwork from several angles.

3. INTRODUCTION TO AIR TRAFFIC CONTROL

Due to Air Traffic Management (ATM) being a high stakes domain where small mistakes can lead to catastrophes and where the human operator and technical systems are working side by side, ATM was chosen as the case for the work within the scope of this dissertation. While the human operator has still the legal responsibility in ATM and where automation at the same time is being introduced more and more to assist in certain tasks, human-automation teamwork in ATM is important to explore to keep the human in the loop of control. SESAR, which *"coordinates and concentrates all EU research and development activities in ATM" (SESAR, 2020)*, wrote in their Masterplan that the vision is to achieve *"high-performing aviation for Europe by 2035"* (SESAR, 2015a). Therefore, it is a huge research interest in automation support for the ATCOs and how to make the operator and the automation work together.

3.1. Air traffic management

ATM is a combined management of air traffic and airspace. It includes air traffic services, airspace management, and air traffic flow management. It involves airborne and ground-based functions and is a collaboration between all stakeholders. As a tightly coupled and dynamic system, the work of individuals affects the work of others, and, therefore, also the overall performance of the system.

ATM is a highly regulated industry in order to manage risks and increase the predictability of actions. The aim is to minimize uncertainties through airspace design, standardized procedures, and coordination agreements between Air Navigation Service Providers (ANSPs).

The term ATM refers mainly to three ground-based functions: Air Traffic Control (ATC), Air Traffic Flow and Capacity Management (ATFCM), and Airspace Management (ASM). ATFCM is a service with the aim to contribute to a safe, efficient, cost-effective and environmentally sustainable ATM system (ICAO, 2019). It is a service complementary to ATC with the objective to ensure the optimum flow of air traffic in areas where traffic demand on occasion exceeds the current capacity of the ATC system. It balances air transport network user demands against ATM system capabilities and ascertains that the traffic volume is compatible with the airports or the airspace. ATFCM has become an important part of ATM regarding how to use the full capacity of the air transport system without risks of decreasing safety.

There are several stakeholders within ATM and the biggest groups are:

- The passengers
- The airspace users – the airlines which can be both scheduled and none scheduled, military and general aviation
- The airport community – the airport operators and ground handling operators
- The ANSPs – the ATC services providers
- The supply industry – the aircraft manufacturers and suppliers of ATM systems. (SESAR, 2006a).

It is widely known that current ATM systems will reach its limits regarding capacity, due to the global increase in flight movements. This will cause negative effects on punctuality and costs. For example, there will be delays which will create enormous costs for the airlines but also costs for the flying public. The pressure on the ATM system is not only due to the direct increase in air traffic. Sequencing and separation of all types of aircraft are also increasing the complexity and difficulties. In addition, there are several stakeholders that need to collaborate. In 2006, in Europe alone, there were approximately 600 airspace sector nodes operated by more than 36 ANSPs (SESAR, 2006a). In 2020, the number of sectors are around 750. This number refers to so called elementary sectors which are normally combined with each other for the sake of efficiency. The constraint to grow is mainly caused by the lack of capacity at airports set by a centrally coordinated slot allocation which determine the departure time and the anticipated arrival time at the destination. It is fair to say that the airspace has reached its limitations, i.e. capacity cannot be increased by adding more sectors (SESAR, 2006a). Adding more sectors may instead increase complexity and workload. In addition, technology is developing that allows the industry to have better and faster aircraft. However, there is also a variety of aircraft in the airspace operating at different altitudes and with different levels of technical equipment. The complexity in the airspace together with the increasing amount of traffic is, therefore, putting pressure on the ATM industry to become more effective.

One solution to increase effectiveness is to introduce automation to support ATCOs in handling the traffic. There is already some automation in ATC today. However, automation in current ATM systems are at a relatively low level (SESAR, 2019). This means that it supports ATCOs' work regarding calculations and traffic flow predictions but does not suggest advanced solutions (at least not in operational use yet). Examples of automation in current ATM systems is that ATCOs can get support regarding conflict detection. It is integrated into the radar screen where the ATCOs have different kinds of conflict detection tools depending on the distance between the aircraft to the conflict, e.g. Medium Term Conflict Detection (MTCD) (Skybrary, 2019a), Short Term Conflict Alert (STCA) (Skybrary, 2019c), and Tactical Controller Tool (Skybrary, 2019d). STCA is a safety net function with the aim to improve the safety of ATC service provision, while MTCD is an operator tool. However, these kinds of conflict detection tools have a low level of automation based on current trajectory information from the aircraft. Another example of automation in current ATM systems are tools that calculate the distance between two aircraft. Calculating the distance between aircraft is a very common and, over time, a cognitively demanding task. A task the ATCO otherwise would calculate manually.

More advanced automation than the above-mentioned ones is the Probe (What-if) Controller Tool (Skybrary, 2019b). It allows the ATCO to test if planned clearances would cause conflicts without making real changes to the system. The ATCO is presented with a choice and if the ATCO chose the If Probe option, the software creates a temporary trajectory and sends it to the MTCD. The MTCD processes the proposed change by the ATCO and provides information to the ATCO about the potential conflicts and what would happen if the clearance would be issued. The ATCO can choose to proceed with the clearance or any other plan the ATCO may have.

Some aircraft are equipped with Controller Pilot Data Link Communications (ICAO, 2016) which is a two-way data-link system by which the ATCOs can transmit messages to an aircraft. It can be used as an alternative to voice communications. In addition, the pilots can visually see the message on a flight deck display.

Due to the limitations on automation support in current ATM environments, significant human effort is still required to manage the traffic. However, with the increase in traffic flow, and the need for a more efficient ATC, automation is constantly developing to assist the ATCO even more. Automation is a key capacity enabler (SESAR, 2019).

3.2. Air traffic control

ATC, provided by ANSPs, is a ground-based service that ascertains an adequate distance between aircraft and other obstacles (such as terrain or other vehicles) in accordance with minimum separation standards. Each country in the world is normally handling the airspace over their own territories, which means that there are many ANSP in the world. Each airspace is divided into sectors, which are volumes of air. Sectors can vary in size and shape depending on the size of the airspace, the number of traffic for a given time period, and traffic patterns etc. In addition, each sector has vertical and horizontal boundaries. The aircraft can fly under two different procedures; visual flight rules (VFR) or instrument flight rules (IFR), depending on the ATCO’s responsibilities.

Standards must be met at the same time as flight schedules and orderly flow of air traffic are maintained. In the beginning, ATC was managed with colour flags for signalling communication from the ground to the pilots. However, the development of technical support systems has rapidly increased and today there are numerous technical devices and digital systems that support the ATCO and the communication between ground and pilot.

Since aircraft from different countries are handled by the same ATCO, there is a need for clear and unmistakeable communication between the pilot and the ATCO. Thus, there is a standardized phraseology, with English as the universal aviation language, which ATCOs working in position (and pilots) must follow to avoid misunderstandings and errors.

There are different kinds of ATCOs depending on where and in what type of ATC facility they work. To simplify ATC (in Sweden), there are two types of ATC environments; area control (which can include both en-route control and terminal area control) and tower control (which can include both tower control and approach control), see Figure 2. These control environments will be described briefly below.

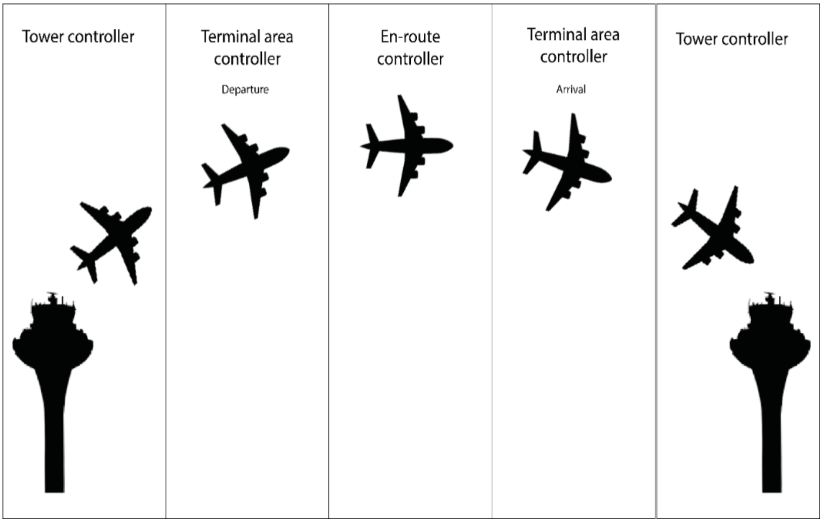

Figure 2. Simplification of air traffic control areas in Sweden (Svensson, Ohlander, & Lundberg, 2019, p. 2).

3.2.1. Area and terminal area control

Area control (or "en-route") is the service provided to aircraft flying between airports. It is generally provided from an Air Traffic Control Centre (ATCC) (see Figure 3). The sky is divided into sectors for different ATCOs to control and the sectors can be divided into different categories based on location and altitude. The main control areas in an ATCC is the area control and Terminal Area Control (TMA) (or "approach control"). Area control is the service provided to aircraft flying between airports, which fly on a high altitude. ATCOs working in en-route sectors transfer aircraft to adjacent en-route sectors, to the TMAs or sometimes provide approach services to smaller airports within their airspace.

In Sweden, ATCOs normally work in pairs in en-route sectors with one Executive and one Planner. The Executive has responsibility for the traffic management within the sector and for the tactical tasks. The Planner is responsible for the planning and coordination of the traffic entering or exiting the sector. Even though the Executive and the Planner work closely together and sit next to each other, they have their own workstation with radar, lists of information of aircraft, weather information, and so forth. They also have a voice communication system where they talk to the pilots, other ATCOs, and different partners regarding the ATC service. In addition, they have, for example, conflict detection tools, e.g. MTCD and STCA, and separation tools.

A TMA, often called approach control, is normally established at the intersection of ATC sectors in the vicinity of one or more major airports. The main function of the TMA control is to guide the aircraft between the control zone (the area around the airport) and the en-route sector. One of the TMA ATCO's task is to sequence aircraft in an orderly manner and transfer (handoff) arriving aircraft to the tower and departing aircraft to the next sector. ATCOs in TMAs tend to have jurisdiction of airspace up to 15.000 feet and up to 50 nautical miles from the airport. Each ATCO has jurisdiction over their specific sector.

ATCOs working in a TMA do not work as closely together as in en-route control (as for example Executive and Planner). Instead, the ATCOs work in groups of two to five people (depending on the amount of traffic). Each ATCO has his/her own workstation with radar, voice communication system, lists of information of aircraft, weather information, and so forth. Just as in en-route, the ATCOs have conflict detection tools (e.g. STCA) and other tools which support their work.

One challenge that differentiates TMA sectors from en-route sectors is that all arriving aircraft to the airport is more or less merging to the same point in the

TMA due to the airspace and airport structure. To support this, ATCOs working in TMAs (depending on the TMA) use decision support tools to sequence aircraft to the merging point before reaching the control zone (e.g. Arrival Managers or Departure Managers).

Figure 3. ATCC in Sweden. Picture from www.lfv.se.

3.2.2. Tower control

The area around the airport, for which the ATCO has the mandate (command), is normally called the “control zone”. The ATCO is handling the traffic in the control zone and on the runway. It can be either aircraft or ground vehicles. Ground vehicles are used for maintenance on and surrounding the runway such as snow sweeping, fixing lights, or checking break actions on the runway. Arriving and departing aircraft fly through the control zone on the way to or from the airport. The work of an tower ATCO is to prevent collisions between aircraft in the sky, on the manoeuvring area (the section of the airport used for take-off, landing, and taxiing) and between aircraft and other obstacles at the airport (van Schaik, Roessingh, Lindqvist, & Fält, 2016). In addition, the ATCO’s work is to expedite the flow of traffic. The tasks have to be performed using visual observations or using radar, and the procedures change according to when the visibility conditions change (ICAO, 2016). Depending on the weather, the location of the airport and the design of the control zone, certain geographical points in the sky can be used for guiding the aircraft in the control zone (Standard Instrument Departure Routes and Standard Arrival Routes).

Depending on the size of the airport, there can be either one ATCO working alone or several ATCOs and ATC assistants working together with different tasks of the airport control (e.g. arrivals, departures, ground control). Each ATCO has their own workstation with air radar, ground movement radar, voice communication system, weather information, etc. In addition to the air radar, some towers at larger airports have ground movement radar that the ATCO can integrate with using a touch table. The workstation in the tower is also equipped with a strip-table. On this table, the ATCOs are placing small paper strips that contains information about arriving and departing flights, so-called "flight-strips". The flight-strips are automatically printed before the arrival or the departure and the ATCO places the flight-strip in the correct column on the strip-table depending if it is an arriving or departing aircraft and in which area of the control zone the aircraft is. There are also strips which the ATCO can use regarding ground traffic; such for example snow sweeping vehicles on the runway. These strips assist the ATCO in knowing where the vehicle is or whether a runway is occupied. Some towers are equipped with an electrical flight strip table, where automation is implemented to print the strips and assist the ATCO in detecting conflicts. Instead of having a small piece of paper, the ATCO has a touch screen as the centre of their working position. The strips are digitalized and appear automatically in one column of the table before arrival or departure. The ATCO can then place the so-called "e-strip" in the correct column depending on if it is an arriving or departing aircraft. There is a safety function in the electronic flight strip table that hinders the ATCO to place an e-strip in, for example, the runway column if there is a ground vehicle in the same column. This function is a safety net, and an assistant to the ATCO to have situation awareness about the current status of the traffic in their sector. In Sweden, only one conventional tower, Arlanda tower, has this kind of electronic flight stripboard at the time writing.

3.2.3. Digital tower control

To optimize tower control, especially for smaller airports with a smaller staff, the concept of digital (interchangeable "remote") towers have been developed (Fürstenau, 2016). A digital tower is a technical solution that makes it possible to provide ATC service for an airport several hundred kilometres away from where the airport is physically located. Although a digital tower ATCO is providing air traffic services to an airport from a remote location, the requirements for this service remain the same.

The workstation in a digital tower is similar to a conventional tower. The ATCO has access to an air radar, a ground radar (depending on the size of the airport), weather information, a voice communication system, and so forth. The window view in a digital tower is, however, digitalized using projects live stream data from the airport. Digitalization of the tower environment paves the way for novel functions and automation support tools, such as presentations of tower heading, zoom functions on the Out-of-the-Window (OTW) view screens object identification, and object tracking. In 2014, LFV, the Air Navigation Services of Sweden, received the operating license from the Swedish Transport Agency for implementing the first operational system (developed by SAAB and LFV). It have a digital ATCO's working position at Sundsvall RTC (Remote Tower Centre) for remotely controlling the traffic at the distant airport of Örnsköldsvik. The system went operational in 2015 (see Figure 4). At the end of 2017, Sundsvall Timrå Airport transferred to being remote-controlled from Sundsvall RTC. During 2018, Cranfield Airport in The United Kingdom and Saarbrücken Airport in Germany went operational with digital towers as well. In addition, the Scandinavian Mountain Airport went operational December 2019. It is the first airport in the world which only has a remote tower, with no conventional tower at the airport.

Figure 4. World's first digitally controlled tower located in Sundsvall, Sweden. Picture from www.lfv.se.

A major benefit of digital tower technology is the possibility to combine multiple digital towers for a single ATCO working position (see Figure 5). The ATCO provides traffic services for two or more airports simultaneously, allowing for an increase in efficiency and reduction in staffing costs. Validation exercises and applied research that has been performed in the framework of the SESAR Joint Undertaking program show that multiple modes of operation can be applied for the simultaneous provision of air traffic control services to two low-density airports by a single ATCO (SESAR, 2015b, 2016). Moreover, while an ATCO may be able to handle two airports at the same time, research has shown that the application of digital tower technologies may increase workload (Kearney, Li, Braithwaite, & Greaves, 2017). To be noted, during the work of this dissertation, no multiple digital tower was in operation in any country.

Figure 5. A multiple remote tower simulator (and also concept) with one airport to the left (pink frame) and another airport to the right (yellow frame).The electronic flight strip table, the radar, the weather screen, and the voice communication system present information for both of the airports. The different screens are usually divided into two parts, one part for each airport.

The aims of multiple digital towers are increased productivity for training, reduced workload for ATCOs, increased cost savings, and more optimized staff schedules. However, to be noted, multiple digital towers are not developed and supposed to be used for all circumstances, for all situations, nor for all airports at the moment. One current target of such towers are smaller airports where ATCOs are working solo in the tower (with maybe one ATC assistant). Instead, remote tower centres could be built with the benefit of cost savings (in the long run), ATCOs having colleagues in the centre working at other airports but in the same building, and ATCOs having ratings for several airports and can, thus, switch tower that can result in optimized staff schedules.

In a digital tower, planning and decision tasks for the ATCO could be assisted by automation to reduce workload and increase situation awareness. However, there are some concerns regarding how to design digital towers, to maintain safety and situation awareness for the ATCO, especially in the context of multiple digital towers. The ATCO working in such tower needs to divide the attention between the airports. While handling movements on one airport, the ATCO needs to maintain situation awareness over the other airport.

ATCOs in both conventional tower and digital towers uses mainly his/her eyes and ears to maintain situation awareness for handling arrivals, departures, and surface and vicinity operations of the runway. Therefore, weather sensors, radar, and flight strips are being digitalized to ease the information presented to the ATCO to increase situation awareness. The OTW, however, is the main source of information for a tower ATCO but can be of limited use during low visibility or bad weather conditions. During such conditions, the ATCO uses displays (e.g. weather presentation, radar, flight strips) and other cues such as asking the pilot about aircraft position (Nene, 2016). This has resulted in many studies investigated in flight labels that are overlaid on the OTW to create an augmented reality of the presentation of the flight information (Saab, 2010; Van Schaik, Roessingh, Bengtsson, Lindqvist, & Fält, 2010; SESAR, 2014; Fürstenau, 2016; Van Schaik, Roessingh, Bengtsson, Lindqvist, & Fält, 2016). In addition, validations have been done regarding automatic tracking by the use of the aircraft's radio signal with an arrow on the top of the OTW screen in which the aircraft will show up (SESAR, 2015c). A study with fifteen ATCOs during passive shadow mode (ATCOs observing live traffic from a distant airport but not having responsible of it or handling it) has shown that ATCOs in a single digital tower prefer labels, regardless of the sensor source from where it was derived, especially during night and low visibility (Van Schaik, Roessingh, Bengtsson, et al., 2016). The use of such labels was found to benefit situation awareness and reduce workload for the ATCOs. However, the ATCOs did not rate the tracking performance good enough to increase capacity. Another example of research exploring enhanced digital functions is the RETINA project (Bagassi, 2017) where augmented reality was investigated to increase the ATCOs' situation awareness.

4. METHODOLOGICAL APPROACH

There is a difference between what operators think and believe about their work and the automation they are working with compared to how they are actually working with the automation. Therefore, the first two studies (Paper I and Paper II) focus on the operators' point of view. It provides an understanding of what the ATCOs desire regarding teamwork, what they believe is lacking, and insights into their experiences. To explore how the ATCOs are actually working with automation is the focus of Paper III and Paper IV. The knowledge contribution of the work is focused on the situations the operators are facing in their everyday work life to capture the operators' perspective on teamwork and automation. To be noted, the most obvious difference between the environments in the studies for Paper III and Paper IV is tower vs en-route. However, the tower environment is more of a digitalised version of a conventional tower whereas the tool being validated in the last study is actual automation. Hence, this reflects much of the ATC domain where many tasks are at first digitalised (the radar, the strip-table) to assist information acquisition and comprehension, while automation comes later to assist decision selection and action implementation. Further details about the methods for each study is found in *5. Summary of papers*.

Conducting studies and planning projects closely linked to reality, while having operational ATCOs as participants, contributes to the external validity of this dissertation. However, working in close collaboration with the industry with different requirements can sometimes also hinder studies. Therefore, in addition to the summary of the methodological approach, this chapter describes a few excluded studies as well. These did not, for various reasons, provide outcomes that could be used as a basis for the dissertation. However, these studies were no failures. Instead, they provided lessons learned with valuable insights about research methods, the domain, and the balance between the two.

Tables 4 presents an overview of the methods used and the number of participants in each study.

Table 4. Methods used and number of participants for each study.

Paper	Main goal	Method	Number of participants
Paper I	Explore teamwork between ATCOs in four current ATC environments	Semi-structured interviews	16
Paper II	Explore ATCOs believes about current and future use of automation and teamwork	Online questionnaire with Likert scale statements and free-text comments	249
Paper III	Explore the differences in work patterns between a conventional tower and a multiple remote tower	ATC tower simulator study using eye-tracking and audio recordings	3
Paper IV	Explore ATCOs' work-as-done with a new automated tool	En-route simulator study using audio and computer screen recordings	2

4.1. Collaborating with the industry

Working in high stakes environments with the focus of the human operators' experience and expectations of teamwork and automation makes it valuable to have operational ATCOs as participants. Hence, during this project, there was a close collaboration with the Air Navigation Services Provider of Sweden (LFV). Through this collaboration, all of the studies included within this dissertation uses empirical data gathered from experienced ATCOs working in ATC. In Sweden, there are approximately 700 operational ATCOs currently working. During the time of this work, a shortage of ATCOs (rather suddenly) emerged in Sweden due to a mix of many ATCOs retiring and the ATCO training being closed for a few years. This affected ATCOs' ability to participate in research studies. Therefore, finding participants for research projects was not always guaranteed due to the need of ATCOs working operational rather than participating in research activities. In particular, large quantitative experiments were not always an option (even when there were interesting quantitative questions that could have been pursued).

It is useful to know the domain and get an understanding of it, to be able to understand the particular "language" and culture of ATC, its population, and its tools. Therefore, during this work, time was spent to get to know the ATC domain. For example, there was the opportunity to enrol in an introductory course to ATM/ATC. In addition, several ATC sites in Sweden and in Europe have been visited during this project, observing work shifts in towers (conventional and remote), approach control, and en-route control. There have been many meetings, workshops, and discussions with managers and ATCOs during the travels to different sites. Moreover, for three of the studies within this dissertation (not including the study in Paper III), ATCOs have been consulted in the planning phase to make sure that the industry, mainly the ATCOs, will have use of the findings.

To conduct studies with domain experts also requires trust between the researcher and the industry (mainly the participants, but also from management). To be able to conduct studies in operational environments, or having ATCOs as participants in studies that might be controversial or that might imply that the ATCOs are being pushed out of their own workstation (by for instance highly advanced automation doing the ATCO work), requires an understanding for the industry and especially of the work the ATCOs are performing. Many ATCOs who have participated within the work of this dissertation has expressed the ATCO work as a craftsmanship. A delicate work that cannot just be overrun by automation with the belief that automation would perform such work better. Therefore, it is of interest, both for the researcher and for the stakeholders, to understand what the operators want and expect from automation and to what the results from research can lead.

It is important to take into consideration that the industry and the research community does not always have the same requirements or research interests. The industry, and in particular the ATCOs or users, does sometimes see problems in a different light than researchers. For example, there might be different requirements during investigations of new tools. For instance, sometimes the ATM industry is interested in implementing new tools whereas the research community is interested in how it is affecting the work. Therefore, the requirements during investigations might differ and this is something the researcher might need to take into consideration when working closely with the industry. According to Rittel and Webber (1973), the problem might not always be given but instead designed by the stakeholders (the industry). This means that the problem might change in character during the solution process. Therefore, Rittel and Webber (1973) argue that the solution is sometimes the problem. Thus, the problem might not always be fully understandable and formulated before it is solved. Therefore, exploring possibilities could provide some insights into the problem (and solution) before deciding on a particular path to take for further research and development.

4.1.1. How working with the industry has shaped the studies

In order to explore how automation could be designed to support human-automation teamwork, it is of interest to explore how the operators perceive teamwork in their everyday work to see if there are any teamwork factors or attribute the operators believe are of importance. Therefore, an interview study, in collaboration with LFV, was conducted in four ATC environments in Sweden: en-route control, terminal area control, tower control for a small airport, and tower control for a large airport (Paper I).

For the study in Paper II, a questionnaire was used to explore how ATCOs perceive automation and teamwork in current and future ATM systems. Since it was of interest to explore differences between countries using to some extent the same technical system (countries being members of COOPANS[2]), a questionnaire was sent out to six different countries. The questionnaire had a mixed-method approach with questions having Likert-scale answers and free-text answers. The close collaboration with LFV built foundation of trust necessary to collaborate with the other members of COOPANS.

The study in Paper IV was conducted in collaboration with SESAR. The data collection for the case study was part of a larger validation simulation where the case study was planned in line with the validation exercises. However, conducting studies in a collaboration like this creates some restrictions in the

[2] An international collaboration between the ANSPs of Austria (Austro Control), Croatia (Croatia Control), Denmark (Naviair), Ireland (Irish Aviation Authority), Portugal (NAV Portugal), and Sweden (LFV).

data collection to fit in with the validation. Due to this, there was limited control over the validation simulation. For example, two ATCOs participated in the case study and the scenarios were predefined by the validation team. However, the case study was planned with this in mind and there was full control over the case study regarding data collection equipment and the analysis method. In addition, the overall validation study was adjusted to the case study as well, influencing, for example, the choice of which sector being used in the case study. The case study was integrated into the validation study with no difference between the validation study and the case study during the actual data collection. Collecting large amounts of data in a high-fidelity simulator provides invaluable data due to the time and money investments. Working with the same ATCOs for several weeks provided also a greater understanding for their work and how they were working. Gathering that amount of empirical data would not have been possible without the collaboration with the industry and SESAR. There were also opportunities, in the bigger validation, to actively take part as a validation assistant. This was done both during the training of the ATCOs and during the data collection to support in the assurance that the right scenario was running, that all participants knew their part, to assist in the data recordings, and so forth.

Conducting studies on how operational automation affects the human operator might also rely on testing in operation. However, it can be dangerous to conduct tests or validations during real operations, especially if the impact on the operator work might not be known (such as increased workload, stress levels, or reduced situation awareness). Hence, many studies require simulators. In addition, to have high external validity and to make simulator studies requires ATCOs, time, and money. The shortage of ATCOs, in particular, was a major reason for not conducting simulator experiments only for the purpose of data collection for this dissertation. Instead, simulator studies (Paper III and Paper IV) were conducted in collaboration with and during other ongoing studies within the industry.

Multiple remote towers, one ATCO controlling two or more airports at the same time (see Figure 6), is a concept which was not in operational use when this dissertation was written. Therefore, two case studies were conducted, one case study in a single tower simulator and one case study in a multiple remote tower simulator (Paper III). The aim was to explore work patterns of ATCOs during different events of handling arrivals. Conducting the study within these tower simulators was a collaboration with the industry, which allowed the data collection to be in highly advanced simulators with high fidelity (Paper III). The simulator for the single tower simulated one of the biggest airports in Sweden and the multiple remote tower simulator was one of the first of its kind in the world, simulating three Swedish airports at the same time.

Figure 6*. Example of a multiple remote tower simulator, presenting one airport to the left (pink frame) and another airport to the right (green frame).*

4.2. High stakes environments

When conducting studies in high stakes environments such as ATC, it is not always possible to conduct the study in the operational environment due to safety restrictions. In addition, the multiple remote tower was a new concept and not in operational use. Hence, two qualitative studies were conducted in simulators (Paper III and Paper IV). In one study (Paper III), eye-tracking was used to capture the eye movements of the ATCOs to explore work patterns of the ATCOs (see Figure 7).

Figure 7. The participant for the study in Paper III was wearing eye-tracking glasses together with a communication recording device.

Adding equipment such as eye-tracking glasses for collecting data could potentially interfere with the ATCOs work (e.g. restricting the field of view), and hence, safety might be compromised. When conducting research in the operational environment, it is important that the work performed is not hindered. However, the aim of using data from real operational environments or having real-time data (as in the simulators) is to get access to and results about the reality. Interfering with the participants (in this case ATCOs) by having them wear special glasses, heart monitors, or inform them about how to act or behave, can, therefore, interfere with the results. However, the advantage of using eye-tracking glasses is that they cover everything the ATCO is looking at, no matter if it is their ATM tools or other persons. This might be necessary when collecting data of ATCOs working in teams or in ATC towers where the OTW view is of great importance and cannot be captured by using mounted eye-tracking. Mounted eye-trackers are attached to screens (see Figure 8) and capture only the eye-movements on the screens which are being recorded. However, the advantage of such eye-tracking is that it is not as intrusive on the participant. Due to the development of eye-tracking equipment over the years and to the fact that the study in Paper III was conducted in a simulator, mounted eye-trackers could now have been used instead.

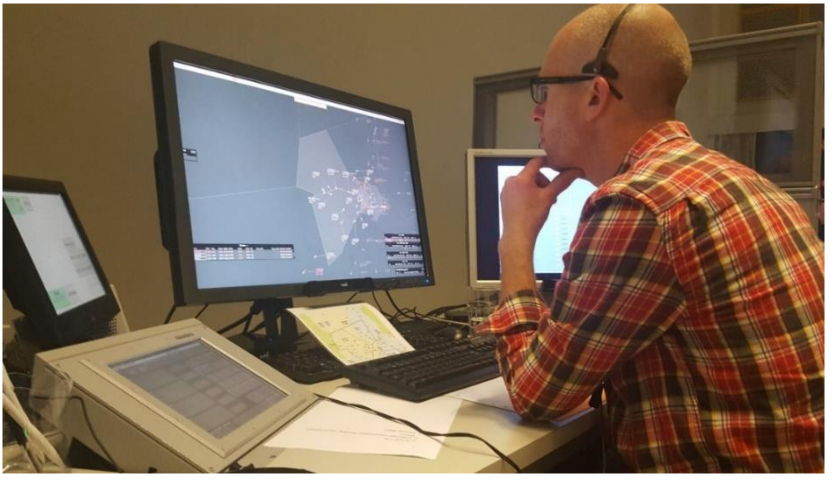

Figure 8. Eye-tracking equipment (in this case Tobii) can be attached to the radar screen (in front of the ATCO).

4.3. Domain experts as participants

Conducting research in close collaboration with the industry creates both interesting opportunities and challenges. Due to exploring the ATCOs' experiences, expectations of human-human teamwork and human-automation teamwork, and how they are actual working with the automation, compared to performance measurements, the number of participants in each study was considered enough to capture the qualities of teamwork. However, having more ATCOs as participants could open up for quantitative studies focusing on, for example, teamwork performance.

In order to achieve external validity, and being able to apply the new tool, function or concept being tested to the real operational environment, the simulators and the scenarios being used need to be realistic and preferably including ATCOs as participants. However, even though ATCOs are used as participants, training before data collection might sometimes be necessary. This for the ATCO to get familiar with the simulator environment or, for example, the new function being tested. In the case study used in Paper IV, where a new automation tool was being validated, the participants (ATCOs) underwent 24 hours of training, spread over eight days, in the simulator in which the simulation was to be held. Since a new tool was being validated, the participants had to learn how to use it before the validation could start. Since the participants had extensive training, they showed signs of learning effects (i.e. participants learned the scenarios and could anticipate upcoming situations). However, during real operations, ATCOs also become familiar with traffic patterns and, hence, change behaviour accordingly to be as efficient as possible. The more secure the ATCOs feel, the smaller buffers (safety margins) they need. The participants stated during the validation scenarios that they used smaller buffers than during normal operations. This occurred especially during the later phase of the validation. This is something that needs to be considered during data collection in general.

Having students as participants might be an option, depending on the research question. On the one hand, students might lack domain knowledge and could, therefore, need extensive training before the data collection can start. Moreover, if the study is conducted in a high fidelity simulator, the time needed for training of students, to be able to do the work of an ATCO in a realistic environment, makes it impractical. On the other hand, recruiting students might be easier since domain experts or participants from the population might be difficult due to small populations or extra costs. Students can be used for basic research where a general phenomenon or behaviour is being explored. However, to study the effect on expert work or expert perspective requires the involvement of actual experts.

4.4. The applied teamwork model

Within the scope of this dissertation, the teamwork model Big Five (Salas et al., 2005) have been used in two studies (Paper I and Paper II). The Big Five model was chosen since it provides a holistic framework for teamwork and since it can be applied to several domains. It is also more detailed compared to other models. In addition, since the Big Five model was successfully applied to other domains, it was believed to fit the purpose of this dissertation to explore teamwork.

Using the Big Five model when creating the questionnaire (Paper II) was considered to be advantageously to compare the results from the study in Paper I with the results from the study in Paper II. Exploring different teamwork models might open up for even more discoveries, especially considering the different ATC environments that have been explored. However, having one single model for several environments made it beneficial to see similarities and differences.

In addition, it was assumed to be an advantage to let the participants for the study in Paper I establish a common vocabulary when talking about teamwork at their work. Therefore, the Big Five model was explained to the participants at the beginning of the interview for them to use the same words when talking about how teamwork can manifest. Although such an approach might hinder interesting comments or discoveries by narrowing down the vocabulary for the participants, the participants were free to speak about teamwork as they wanted.

4.5. Initiative to other studies and lessons learned

In addition to the two qualitative simulator studies (Paper III and Paper IV), a quantitative simulator study was planned. One reason for having a quantitative study was to collect data from many ATCOs at the same time to find patterns in their way of working. The aim of the study was to explore how ATCOs were working with a new overlay on the OTW view. The reason was that many ATCOs have addressed the interest to use labels as an overlay on the OTW view in towers to get information about the flights, instead of looking at the strip-table. There is already some research regarding augmented reality of the presentation of the flight information (Saab, 2010; Van Schaik et al., 2010; SESAR, 2014; Fürstenau, 2016; Van Schaik, Roessingh, Bengtsson, et al., 2016). However, there was a plan for exploring how the use of labels affect ATCOs in relation to human-automation teamwork.

Working closely with the industry while aiming at high external validity includes also some challenges such creating realistic simulations. For example, the simulator which was supposed to be used was not delivered in time for the study. In addition, there was a shortage of ATCOs, meaning that there could not be any ATCOs participating in this particular study at the time. Hence, the label study had to be cancelled.

However, the label study resulted in several insights. Firstly, conducting research with domain experts and operational ATCOs require studies conducted in the correct environment, by in this case have high fidelity simulators, to be able to draw any useful conclusions. In addition, during the planning phase of the study, discussions were held with ATC experts and ATCOs about the reason for having labels on the OTW view. It resulted in a realisation that it is of interest to first know and to understand what the ATCOs believe will happen in the future before designing and implementing automation. Moreover, what the ATCOs and the industry want out of the automation before automation is developed and tested. Therefore, the planning of this study contributed to the questionnaire study (Paper II).

Another study that provided valuable insights was a collaboration study together with COOPANS. It was an opportunity to collect eye-tracking data at six different ATC sites during a validation of new colours of the radar screen. Due to the shortage of ATCOs, collecting data from both Planner and Executive at the same time in several different countries was a rare opportunity that could result in several interesting and useful findings for both industry and the research field regarding teamwork. However, the case study within the colour validation had to be cancelled due to language barriers and operational differences at the sites. Due to an attempt of keeping the reliability of the validation, the participating ATCOs spoke their native language (and not English) with each other during the data collection since it is a normality at some sites. The idea of conducting research at operational sites with licensed ATCOs is to gain as realistic data as possible. Hence, having participants speak another language than their native language could affect how they were interacting and collaborating with each other, the results and, thus, affecting the purpose of the case study. Translating the data within the time frame of the project was not possible. In addition, even though it was planned for to collect data from both Planner and Executive when they worked together in the same sector, one of the sites for the data collection did not have the role of the Planner in their en-route sectors, meaning that the intentions for the case study could not be measured at that specific site.

However, even though the data collection did not progress as planned, some data was still collected and analysed. Firstly, it resulted in a poster publication presented at a conference regarding collaboration between Executive and Planner. Secondly, and most important, it resulted in the realisation that it was of interest to first explore the teamwork between Executive and Planner through their own descriptions. Therefore, the interview study in Paper I was conducted to have the ATCOs explain how they perceive teamwork as a means to introduce automation and human-automation teamwork. Hence, the results from the interview study, in addition to the insights from the label study, lead to the questionnaire study in Paper II.

5. SUMMARY OF PAPERS

This section provides an overview of the papers included in this dissertation. Each paper is presented with an introduction to the purpose of the paper, the method used, and the conclusions that can be drawn. The full papers can be found at the end of the dissertation.

5.1. Paper I

Svensson, Å., Ohlander, U., & Lundberg, J. (2019). **Design implications for teamwork in ATC**. Cognition, Technology & Work. doi:10.1007/s10111-019-00579-y.

Participation: For this paper, I together with the second co-author planned the execution of the project. We collected the data together through the interviews as well as analysed the data. I had the main responsibility for writing the paper.

5.1.1. Introduction

In order to be able to design automation and cognitive systems supporting teamwork in ATC, lessons can be learned from how teamwork between ATCOs are perceived in current ATC environments. This can be achieved by exploring if there are any teamwork factors or attributes the operators believe are of importance for effective teamwork. If any specific teamwork factors are identified as important for effective teamwork, it could be of interest to further explore them regarding human-automation teamwork as well. Therefore, to get an understanding of how ATCOs perceive teamwork in current ATC environments, interviews regarding different teamwork factors were conducted in four different ATC environments. The Big Five model (Salas et al., 2005) was used as a foundation for the interviews (see Section 2.1).

5.1.2. Method

The study consisted of interviews with a total of 16 experienced ATCOs working at four different ATC environments: en-route control, TMA, tower control for a smaller airport, and tower control for a larger airport in Sweden. Four ATCOs from each control environment were interviewed.

During the interviews, each participant made a short description of how they would describe teamwork in relation to their work environment. Then, the participant ranked the eight factors from the Big Five model, from the most important teamwork factor to the least important teamwork factor, and explained the reasoning behind the ranking. The participant then selected five behavioural markers from the Big Five model of which the participant found most relevant for their team. The interviews were transcribed and coded into different themes in relation to the factors from the Big Five model.

5.1.3. Conclusions

This study showed that all teamwork factors were of importance for the ATCOs working together in their current ATC environments with *mutual trust*, *adaptability,* and *shared mental models* as the top-ranked teamwork factors. *Team leadership* was ranked as the least important teamwork factor. However, the teamwork factors are manifested in different ways in different ATC environments and participants at some environments believed that *team leadership* is of great importance while other participants from other ATC environments see the team leader as more of a supportive role.

Teamwork is important during both routine operations as well as during stressful or abnormal situations. For example, *mutual performance monitoring* becomes increasingly important during stressful situations. However, the ATCOs stated that during those situations, *mutual performance monitoring* decreased since the ATCOs focuses on their own tasks, and do not have time to listen to the sound in the room or check what the other team members are doing.

The teamwork factors manifest in different ways carrying out different tasks. However, all eight factors from the Big Five model were considered to be relevant. Important to consider is that the design of the organization, the environment, and the tools, affects teamwork and the importance of the different teamwork factors. An important finding for designing future ATC systems.

The main contributions of this paper are:

- All teamwork factors from the Big Five model were considered important in all ATC environments.
- It is important to design for efficient teamwork that works during both routine operations and stressful or abnormal situations.
- It is suggested that design research (of for instance workstations) should focus on supporting the most important teamwork factors.
- The design of the organization, the environment, and the tools, affects teamwork and the importance of different teamwork factors. This needs to be considered if changing the workstation for the ATCOs.

5.2. Paper II

Svensson, Å., Lundberg, J., Forsell, C., & Rönnberg, N. **Automation, teamwork, and the feared loss of safety – Air traffic controllers' experiences and expectations on current and future ATM systems**. Submitted to ECCE2020: European Conference on Cognitive Ergonomics.

Participation: For this paper, I had the lead in the planning of the project. For data collection, COOPANS assisted in distributing the questionnaire to the ATCOs and my co-supervisor assisted me in the data analysis. I had the lead and wrote the greater majority of the paper.

5.2.1. Introduction

With the introduction of automation comes also the introduction of human-automation teamwork for the operator to stay in the control loop. However, investigations regarding operators' believes about future automation and how it might affect safety is necessary for the design of future ATM systems to maintain the human operator in the control loop. Teamwork between the ATCO and the automation might contribute to keep workload within acceptable limits and increase situation awareness. In addition, automation as a team member could decrease automation surprise, and, hence, enhance performance. However, human-human teamwork and human-automation teamwork can differ and different teamwork factors might be necessary. Successful teamwork with automation is also due to the attitude of the operators regarding the automation and the current work environment. If the automation is not well-designed to support human-automation teamwork, and if the operators are not accepting of the automation, automation surprise and, hence, disastrous consequences might arise. Therefore, involving the operators in early development phases and exploring what kind of teamwork that is of importance for the operators might aid the design of automation. Hence, this paper focused on ATCOs' experiences and expectations regarding current and future automation, safety, workload, situation awareness, and teamwork to understand the underlying need of the operator.

5.2.2. Method

An online questionnaire was distributed through ATM managers to ATCOs in six different countries: Sweden, Denmark, Austria, Croatia, Ireland, and Portugal. The questionnaire was distributed to area control, approach control, and tower control. In total, 249 licensed ATCOs answered the questionnaire. Due to the fact that the questionnaire was distributed to ATCOs working in different ATC sites, hence, in different teams, the Big Five model (the same as in Paper I) was used since it can be used regardless of the type of team and domain (Salas et al., 2005).

The questionnaire consisted of a total of 139 questions and statements split into five sections. Two sections regarded ATCOs' experience in today's ATM system regarding the grade of automation, safety, workload, and situation awareness, and their expectations for the future. Two sections regarded teamwork factors from the Big Five model for human-human teamwork and human-automation teamwork. One section regarded questions about gender, age, country, and endorsement. The statements were answered using Likert scales ranging from 1 = "very low" or "not at all important" to 5 = "very high" or "extremely important" as well as optional free-text sections. Statistical analysis was performed for the Likert scale answers and a thematic analysis was performed for the free-text answers.

5.2.3. Conclusions

This study showed an expected higher grade of automation in the future compared with today amongst ATCOs while workload was expected to stay at the same level. Safety was expressed to increase in the future. However, only as long as nothing unexpected happens and everything goes as planned.

This study has shown that human-automation teamwork is central to ATCOs' view of increased automation where automation was seen as a safety net and a benefit. The ATCOs expressed a fear of being a backup system to the automation with the expectation to take control if the automation would no longer be able to manage the situation.

Deskilling and being out-of-the-loop, due to only monitoring the situation and having to intervene when the automation is unable to manage the situation, were two of the most common reasons for this fear of decreased safety. Due to its outstanding safety record, the ATM community should see this as wake-up call.

The main contributions of this paper are:

- While automation is expected to increase in the future, safety is expected to increase as long as everything works as imagined. However, there is a fear that the roles of the ATCO and the automation would switch, making the ATCO a backup system of the automation. Research is needed to prevent this change in roles.
- There is a risk, and an expressed fear, that the ATCO would not be able to take control from the automation if necessary, due to being out-of-the-loop and decreased situation awareness. More research is needed regarding how automation can be designed to keep the operator in the loop of control.
- New operational procedures and training in regard to automation is necessary for the ATCOs to maintain operational skills while working with automation.
- It is suggested to design automation to include more teamwork aspects, such as *adaptability* and *mutual performance monitoring*.

5.3. Paper III

Svensson, Å., Forsell, C., Johansson, J., & Lundberg, J. (2017). **Analysis of work patterns as a foundation for human-automation communication in multiple remote towers**. In Proceedings of the Air Traffic Management Research and Development Seminar, Seattle, Washington, USA.

Participation: The planning of the project had already started when I was introduced to the study. Therefore, I took only a minor part in planning but was part of the data collection for both of the case studies. My main contribution in this project is the data analysis and I had the lead and wrote most of the paper.

5.3.1. Introduction

In order to be able to design for human-automation teamwork in ATC, it is useful to understand how ATCOs are working in current environments to be able to compare this with a (not so far into the) future scenario. Research regarding multiple remote towers (one ATCO handling more than one airport at the time) has recently increased and the interest for optimizing smaller airports into a control centre has been the focus for many researchers for a while now. However, more airports mean more information for the ATCO to handle at the same time. Due to the increased information and functionality in a multiple remote tower (Meyer & Fricke, 2016), and hence, workload (Fürstenau, 2016) when handling more airports, it can be assumed that the ATCOs will need more assistance and decision support from higher levels of automation. In addition, the ATCO and the automation working as a team need to know each other's respective tasks and actions without spending valuable time on interpretations or explanations. Thus, for such teamwork to be efficient, the work patterns of the ATCO, such as how the ATCO is working and in which order the ATCO focuses on different parts of the workstation, could be visible for the automation. If so, the automation could make use of the work patterns, predicting the ATCOs actions and give situation based support. In addition, if the automation and the ATCO would know more about what the other team member is doing (*mutual performance monitoring*), the automation can be designed to support efficient implicit communication, meaning what humans and systems do without verbally expressing it. Implicit communication might enhance human-automation teamwork. Therefore, this study aimed at comparing ATCOs work in a current tower environment with a future multiple remote tower controlling three airports.

5.3.2. Method

Two case studies were conducted. One case study in a single tower simulator controlling one airport and one case study in a multiple remote tower simulator controlling three airports. Eye-tracking was used to capture the eye movements of the ATCOs and reveal work patterns. Both case studies were conducted using ATC simulators due to the fact that the use of eye-trackers in real ATC towers requires safety validations of the eye-tracking equipment. Since it was not possible to conduct such safety validations at the time of the study and since multiple remote tower was a new concept and was still not in operational use during the time of the study, ATC simulators were used.

One licensed ATCO participated in the single tower simulator and two licensed ATCOs participated in the multiple remote tower simulator. All participants had worked in the simulator before and were familiar with the situation.

For both case studies, episodes of 15-30 minutes from the recorded scenarios containing arrivals were the focus of the analysis. Comparisons were made between the different episodes and the different tower environments to investigate and establish if there were any patterns in the ATCOs' way of working with arrivals. The comparison consisted of what the ATCOs were looking at, in which order, and what they were saying. During the analysis, an arrival was classified into three different *events*; "continue approach", "clear to land", and "taxi". During the main events, activities performed by the ATCO were captured and analysed.

5.3.3. Conclusions

The results from this study have shown that even though the overall work tasks for the ATCOs working in a conventional tower or working in a multiple remote tower are the same, the ATCO in the multiple remote tower needs to handle more information at the same time. In addition, the ATM system in the multiple remote tower does not provide more supportive information about the traffic situation to the ATCO and does not have more information about the ATCO compared to the conventional tower. However, the ATCO in the multiple remote tower is handling three airports at the same time instead of only one. Therefore, involving higher levels of automation for monitoring, decision making, and as cognitive support for the ATCO might increase efficiency.

The increased amount of traffic and the increased complexity could be easier to handle with support from and teamwork with automation. This paper gives reason to believe that the potential to have more than one airport or more complex or intense traffic depends on the quality of human-automation teamwork. Even though the multiple remote tower simulator is more complex than the conventional tower, with current designs there is a lack of implicit communication between the ATCO and the system where the ATCO has to manually find and interpret information. However, it is important the ATCO and the system can communicate implicitly to make the work more efficient for the ATCO, not having to double-check information from the system and to strengthen the teamwork between the ATCO and the ATM system. Hence, implicit communication might lower the workload for the ATCO. This study has shown that there are opportunities for a future with situation-based support with implicit communication between the ATCO and the ATM system. The human-automation teamwork could be strengthened, through the use of work patterns, which can result in enhanced performance.

The main contributions of this paper are:

- There is great potential for implicit communication between the ATCO and the ATM system, based on work patterns, to increase efficiency.

However, work patterns must be clear and regular for the automation to use.

- Work patterns of ATCOs differ between the conventional tower and the multiple remote tower, something that needs to be considered during the design phase of the automation.
- Eye-tracking, as used in this study, could be complemented with data regarding ATCOs interactions with the ATM system or the verbal communication between the ATCO and the pilot for finding clearer patterns.
- The quality of human-automation collaboration affects the potential to have more airports than three (as in this study) or more complex or intense traffic.
- The design of the environment will affect the work patterns, which could in turn affect the support from the automation.

5.4. Paper IV

Svensson, Å., Lundberg, J., Forsell, C., Rönnberg, N., & Alfredson, J. **Boundary Awareness and Automation Degradation: Realistic human-automation work episodes in air traffic control**. Submitted to the Journal of Cognitive Engineering and Decision Making.

Participation: For this paper, I had major parts in the planning of the project, the data collection for the case study, analysis of the data, and of writing the paper.

5.4.1. Introduction

This paper proposes a new concept, Boundary Awareness (BA), to understand how automation is affecting the work of operators. Adding automation in ATC means that the operator’s need for understanding the situation, to have Situation Awareness (SA), extends to include both monitoring and controlling task of the traffic but also monitoring and controlling the automation. This means that automation adds the need to monitor the boundaries of automation performance and the effects of the current situation on automation as well, i.e.

its performance envelope. The analysis indicated that BA, an aspect of team SA (Mica R. Endsley, 1995), was key to the ATC episodes captured when ATCOs were working with automation. The paper shows that it is of importance to understand how operators actually work with automation and how BA can contribute to foresee the status of the automation and the knowledge of what the automation can or cannot manage.

5.4.2. Method

In order to explore boundary awareness in ATC, a qualitative case study with an inductive approach was conducted during a broader ATC simulation conducted by SESAR (Rydell, Matsson, Stibor, Id, & Rappich, 2015). The focus of the simulation was a new automated arrival management tool (Extended Arrival Management with Controlled Time of Arrival (CTA) and a 4-dimensional profile (3D + time)), i4D. The case study took place in an en-route simulator with two experienced ATCOs. The broader simulation, hence also the case study, took place during eight days with three scenarios per day. Each scenario was 90 minutes.

Through episode analysis (Korolija & Linell, 1996; Svensson, Forsell, Johansson, & Lundberg, 2017), five episodes (four episodes to relate to one baseline) were identified as interesting for in-depth transcription and further analysis for the case study. In the baseline (Episode 1), a CTA time was given but i4D was not activated. The four other episodes consisted of two episodes when the automation (CTA with i4D) worked as supposed (Episode 2 and 3) and two episodes when an irregular situation occurred (Episode 4 and 5), resulting in automation degradation. In Episodes 2 to 5, CTA with i4D was activated.

5.4.3. Conclusions

This paper describes how work is actually performed by ATCOs interacting with automation (and degraded automation). The case study showed how introducing more automation changes the ATCO work. Implementing automation as within the case study, the ATCOs task changes to monitoring the automation performance instead of actively controlling of traffic. When automation was working as-imagined, there were fewer control actions, less information delivered for manual control, and fewer interactions with aircraft than without automation or during degraded automation.

During the analysis, the new notion of BA (or rather the lack of it) stood out as central. Therefore, within the paper, the notion of BA is proposed as necessary when working with automation. Boundary awareness is defined as *the ability of an operator to know the current situational conditions that can affect automation performance, the current status of automation performance boundaries, and the resulting automation performance*. BA is related to SA and team SA. However, as a teamwork aspect, BA is narrower than team SA and becomes increasingly important with increasing automation. The paper argues that transitions of automation levels require a stronger BA, strengthening both the ATCO's awareness of automation sensitivity to external conditions and the ATCO's awareness of the actual conditions. Stronger BA would also reduce the mode confusion in dynamic situations. Therefore, it can be assumed that having BA with functioning automation, the ATCO could, for instance, handle more traffic at the same time or more time for planning. It is argued that strengthening BA could make automation degradation management more proactive.

The main contributions of this paper are:

- Introducing automation affects the operator work to a more monitoring role than of an active controlling role.
- When working with automation, the awareness of the situation needs to be extended to the awareness of the boundaries of the automation as well.
- Boundary awareness is necessary to have knowledge about the boundaries of the automation and their effect on the work situation to make the work of the operator more proactive.
- Research regarding boundary awareness should continue regarding designing automated systems.

6. DISCUSSION

The overarching aim of this dissertation was to explore human-human and human-automation teamwork within the cognitive system of ATC from a human factors design perspective. To fulfil this aim, four studies (presented in four papers) explored teamwork and automation in ATC from several perspectives. The discussion provides an interpretation of the work within the four papers with additional reflection and analysis of the whole. Conceptual design possibilities for how to strengthen human-automation teamwork are discussed. The results from this dissertation are for researchers, designers, and developers of automation to consider during the design and development phase of automation. The results can also lay as a foundation for further design research within the area of human-automation teamwork.

This work contributes with an understanding of how operators work with other humans (Paper I) and how the ATCOs work with the ATM computer system (including automation) in current ATM environments (en-route, approach, and tower control) (Paper II, Paper III, and Paper IV). The reason for this was to understand which positive teamwork aspects to enhance and what to redesign or introduce in future ATM systems. The work conducted within the frame of this dissertation has not only led to the discovery of two teamwork aspects (implicit communication and boundary awareness) that can contribute to effective teamwork. It has also identified certain challenges and current problems with automation, a consequence from the explorative frame used for the work within the scope of this dissertation. It is in particular when something goes wrong, with for example the automation, the need for a change of work, procedures, and designs become visible.

6.1. What are the operators' apprehensions?

Even though it was identified that ATCOs have teamwork with each other (Paper I) and that teamwork is believed to be important when working with automation (Paper II), automation surprise still occurs (Paper IV) due to the lack of knowledge of the automation, its boundaries, and human-automation teamwork. The results showed also a fear of decreased safety in ATM in the future (Paper II). The ATCOs believed that the grade of automation will increase and that workload will stay at the same level as today. One reason for this could be, and as the ATCOs' expressed (Paper II), that the traffic density and the traffic complexity will increase in the future, something that the ATM community have predicted (SESAR, 2006b, 2019).

Having automation creates the potential to handle more traffic at the same time. However, when the automation is failing for any reason, the ATCO might end up with even more tasks and workload than expected (Paper IV). If the traffic is then also increased compared to the traffic load today, it can be assumed that the ATCO would have a hard time resuming control over the situation when automation is failing. There are reasons to believe that this is a real threat. Potential solutions and suggestions for automation tools to cope with the increased traffic density is proposed (SESAR, 2017, 2019). However, due to the increased grade of automation, there is a potential to increase the amount of work, meaning that the workload will continue at the same level as today even though there is automation to assist the operators.

Previous research have showed that there can be resistance among ATCOs regarding the increasing automation in their work (Hilburn & Flynn, 2001). There are many factors that can contribute to their attitude such as age, experience, and job satisfaction (Parasuraman et al., 1998; Nijhuis et al., 1999; Eurocontrol, 2000; Thompson & Bailey, 2000; Eurocontrol, 2004; J. D. Lee & See, 2004; Bekier, 2013; Mirchi et al., 2015).

Within the scope of this dissertation, ATCOs have expressed that certain tools that the ATCOs can use to ease their work are not being used due to poor design, bad function of the automation, and that ATCOs have incomplete knowledge about the automation and its benefits etc. For example, many ATCOs participating in the research work for this dissertation are united in the opinion that the Conflict and Risk Display (where MTCD and STCA are presented) the ATCOs use to identify conflicts contains too much information. ACTOs have expressed that the MTCD provides false alerts which takes unnecessary attention from the ATCO (Lundberg, Svensson, Josefsson, & Johansson, 2015; Svensson, 2015).

In addition, ATCOs turn off the automation when there is a lack of knowledge about it and when it does not work as expected (Paper IV). Further, the ATCO ends up with more work when the automation is used and then turned off than if it was not used at all (Paper IV). In that case, instead of supporting the ATCO, the automation adds additional taskwork to the ATCO, contrary to the intention of the implementation of the automation. Moreover, the expressed fear of ATCOs being a backup system to the automation (Paper II) with the purpose to take control from the automation when the automation cannot longer manage the situation is something which happened in the study for Paper IV. The ATCO became the backup system since the ATCO got a monitoring role with increased automation and had to recover the situation when the automation could no longer manage the situation (Paper IV). Consequently, the scepticism towards automation is understandable due to state of the existing, or the lack of, automation support.

The qualitative results (Paper II) indicated that the ATCOs feared that automation will take control from the ATCO. This might lead to decreased situation awareness, as the quantitative results showed (Paper II). This is pointing towards a risk for an out-of-the-loop problem and that ATCOs will not be able to take over control from the automation when necessary. However, the ATCOs expressed that they do believe that safety might increase with automation as long as the automation is working as expected. It is when something goes wrong, or when the ATCO is being out-of-the-loop, they fear a decreased safety (Paper II). These are worrying results and something control system domains (such as ATM but also other domains as, for instance, train control and nuclear power plants) should take seriously. Therefore, it is important to conduct studies of work-as-done (S. Dekker, 2006) with automation in realistic settings when the traffic amount and the different conditions shifts over time, to truly understand how the work with the automation is functioning when the traffic picture is changing (as done in the study for Paper IV).

All of the mentioned effects due to automation might contribute to the fear of future automation. One reason for these negative effects might originate from a lack of teamwork between human operator and automation in existing systems. In addition, there is a lack of knowledge about how the automaton is working (as shown in Paper IV) and inefficient communication with the automation (as shown in Paper III). These issues are also design openings. If, for instance, human-automation teamwork would be stronger, through human-centred designs of the automation based on the teamwork factors, the fear of automation might decrease due to a more well-functioning work system.

6.2. Towards human-automation teamwork

While the human operator is still responsible for the procedures, automation should be designed from a human-centred point of view to reduce automation surprise and, hence, maintain safety. The capabilities and limitations from both the operator and the automation could be used in the design of the automation, not only to divide the work tasks between the operator and the automation. The sum of their capabilities of working together might be more efficient or safe than their individual parts. Some research have already investigated the importance of human-automation teamwork (Hutchins, 1995; Charles E Billings, 1997; Christoffersen & Woods, 2002; D. Norman, 2017), and the differences and similarities between human-human and human-automation teamwork (Nass, Fogg, & Moon, 1996; P. U. Lee, 2005; Oxstrand et al., 2013). Having human-automation teamwork in ATM might enhance performance while maintaining a high safety level. However, to concretise *what kind* of teamwork the ATCOs believe are of importance, Paper I and Paper II showed that *mutual trust, adaptability, shared mental models*, and *mutual performance monitoring* were the top-ranked teamwork factors in ATM for both human-human and human-automation teamwork. It is, however, not as simple to only transfer these findings into design guidelines to provide the automation with more of what the operators' ranked highest. It is important to understand the reasons to why certain teamwork factors were seen as important or less important with reference to e.g. the work task and the environment. Having a clearer understanding of the underlying reason for why some teamwork factors are of more importance (than provided in Paper I and Paper II), the automation could be designed to support specific aspects or support in certain situations.

A core property of ATC points toward one reason to why *adaptability* was ranked as one of the most important teamwork factors for both human-human teamwork and human-automation teamwork. It might be due to the rapid changes in the traffic flow in all of the ATC environments. Having a contingency plan is crucial due to the short time horizons, especially in stressful situations (Paper I) where time for planning can be lacking. Even though automation is implemented to support the ATCO, the workload for the ATCO is predicted to be at the same level as today (Paper II). Therefore, the situations where having a contingency plan is crucial will most likely remain. It is assumed that designing automation to be adaptive can enhance effectiveness and productivity for the team, which goes in line with previous work (M. W. Scerbo, 1996; Calefato, Montanari, & Tesauri, 2008).

Since the top-ranked teamwork factors do not differ much between human-human and human-automation teamwork, applying human-human teamwork models to human-automation teamwork could be a good starting point for design in the case of ATC. However, it is important to notice that when designing for teamwork in ATC, some teamwork factors might have implications for design for different "levels" within ATM (Paper I): the organisational structure, the ATC environment, and tools and functions. Certain teamwork factors affect some levels more than others do (Paper I). For example, the teamwork factors *team leadership* and *shared mental models* can be addressed at the organisational level, depending on if the team needs a clear leader or if the team needs certain ways of working. However, for human-automation teamwork, *team leadership* was ranked as the least important factor. Hypothetically, automation might be seen as a team member where the tasks of the team leader are not allocated between the human and the automation. Instead, the human operator and the automation work together, in comparison to having a support role as the team leader was in the en-route environment (Paper I). To strengthen this analysis, further research is necessary. Moreover, it is recommended to investigate the lowest-ranked teamwork factors for both human-human and human-automation teamwork (Paper I and Paper II) to understand why some factors are considered to be less important than others are.

Designing for the teamwork factor *closed-loop communication* might affect the ATC environment, the tools the ATCOs would use, and the workstations of the ATCOs and, hence, the operational work (Paper I and Paper III). For example, if the workstation is designed in a way that allows unhindered communication, acknowledgements of messages without the need to double-check the information, and support for *mutual performance monitoring*, it can affect the team's performance (Paper III). As the results from the study in Paper III implies, which has also been reported by Rognin and Blanquart (2001), designing the workspace and the automation to support implicit communication can positively affect the efficiency and the dependability of the system. Tools or functions that, for example, allows the team members to have *mutual performance monitoring* or *adaptability* would also affect the operational work (Paper I).

Backup behaviour was seen as the least important factor for human-automation teamwork (Paper II), a result which differs from current human-human teamwork (Paper I). One reason for this result might be that since there is, or at least has been, a scepticism towards automation (Hopkin, 1995; Hilburn & Flynn, 2001; Borst, Westin, & Hilburn, 2012), ATCOs might not want to have automation as a backup. However, many automation functions in current ATC systems can be seen as backup systems, e.g. tools such as STCA. If the ATCO is not aware of a pending conflict, the STCA will alert the ATCO about it. Therefore, why the responses turned out like this is something that needs to be further explored. In contrast, ATCOs expressed a fear that they will end up as the backup system to the automation in the future (Paper II). They believed that automation is predicted to increase to the extent that it will take control tasks from the ATCO, leaving the ATCO to only monitor the automation instead of controlling the traffic. Tendencies towards ATCOs being the backup system to automation could be seen in Paper IV. When the automation was working as expected, the ATCO monitored it and intervened only when something went wrong. These kinds of work-as-imagined and work-as-done studies should be in the pipeline for further investigation.

6.3. Two teamwork aspects

To enhance teamwork with automation in ATC, the work within the scope of this dissertation has identified two teamwork aspects, which at the moment are lacking when working with automation in ATC. Firstly, *implicit communication* is proposed to make the communication between the operator and the automation more efficient compared with today. Secondly, *boundary awareness* is proposed to increase the operator's knowledge about the automation, its boundaries, and the consequences when it goes out of the boundaries. Figure 9 is an illustration of how boundary awareness and implicit communication are related to the other teamwork factors based on Figure 1, a version from Salas et al. (2005).

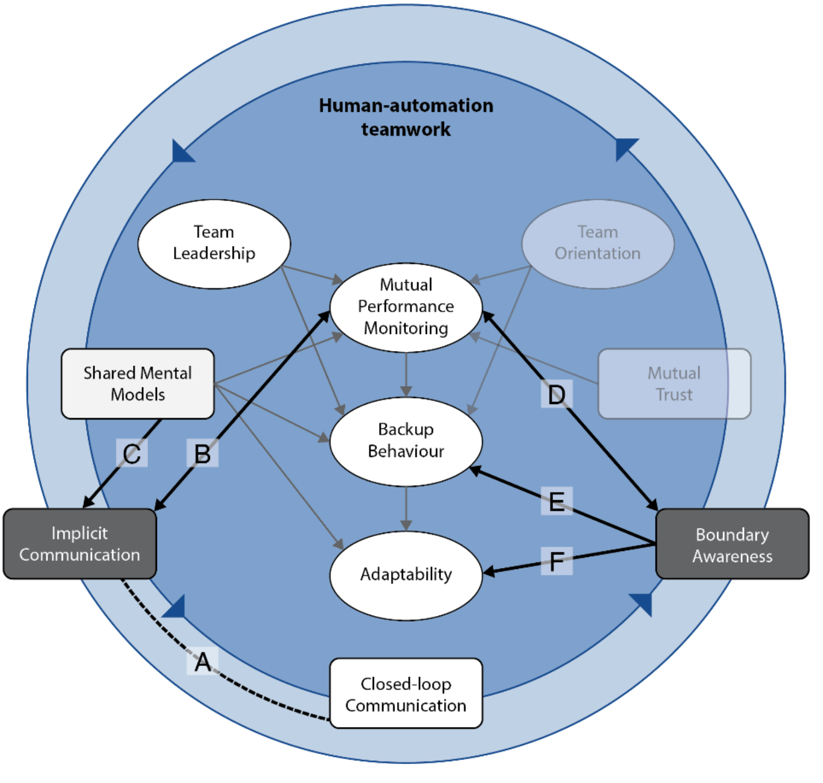

Figure 9. All teamwork factors for human-human teamwork are still relevant for human-automation teamwork but with the necessary complement of implicit communication and boundary awareness that affect the other teamwork factors.

Implicit communication and boundary awareness are derived from the Big Five model (Salas et al., 2005) as a foundation for teamwork together with the results from the work within the scope of this dissertation. Figure 9 illustrates the teamwork factors used for human-human teamwork applied to human-automation teamwork. Hence, for human-automation teamwork, *mutual performance monitoring*, *backup behaviour*, and *adaptability* are still core functions. *Team leadership* is important to keep the ATCO in control and in command for the airspace and the control zone. *Shared mental models* are also important to work towards the same team goals in accordance with established procedures. *Team orientation* and *mutual trust* are two teamwork factors from the Big Five model that have not been as extensively explored within the scope of this dissertation. Trust was not in focus due to the already extensive research (Muir, 1994; Bonini et al., 2001; Eurocontrol, 2003; Bekier, 2013; Chavaillaz, Wastell, & Sauer, 2016; de Visser et al., 2016) while *team orientation* can be seen more like an attitude rather than a behaviour compared to the other teamwork factors (Salas et al., 2005) (Paper I). Not having *team orientation* makes it almost impossible to establish teamwork in the first place (Salas et al., 2005). Hence, ATCOs expressed team orientation as a prerequisite for ATC work (Paper I). The ATCOs also expressed that "solo players" do not belong in ATC and are dismissed from the initial training if they cannot work in teams (Paper I). Therefore, this dissertation has not focused as extensively on these two teamwork factors.

Boundary awareness and implicit communication are added in a layer outside of the Big Five model since, within the work of this dissertation, these two elements have been identified as needed for human-automation teamwork. The Big Five model was created for human-human teamwork, and even though it can be used to enhance human-automation teamwork, the findings from the work within the scope of this dissertation propose that boundary awareness and implicit communication might strengthen human-automation teamwork. The following sections discuss implicit communication and boundary awareness and their relationship towards the other teamwork factors using Figure 9.

6.4. Implicit communication

With the increasing complexity in ATC and with more aircraft to control, the information flow to the human operator is also increasing (Meyer & Fricke, 2016). For example, working in a multiple remote tower controlling more than one airport at the same time creates an increase in information acquisition and information comprehension for the ATCO. Even though there are more airports for an ATCO to handle in a multiple remote tower, the way of working is, in current concepts, similar to a tower with one airport (Paper III). The multiple remote tower do not have more functions or decision support tools to assist the ATCO to cope with the increased information (Paper III), although several projects are investigating new functions (see Section 3.2.3). Instead, the ATCO just have more work. Therefore, it becomes more important that the information is visible and useful for the ATCO. The ATCO is not supposed to chase the information, as it is the case in today's systems (Paper III). Since communication is especially important when the complexity of the environment increases (Salas et al., 2005), it is proposed within the scope of this dissertation that the ACTO and the ATM system should communicate in a more implicit way to decrease the explicit interaction with the system (Paper III). This follows the work of Eggeling et al. (2015) who used hidden data signs (e.g. body language) to detect operators' decisions to potentially predict the next actions of a user by an automation.

Compared to implicit communication, *closed-loop communication* means to not only give clearance or a message to someone (or something) but also that the receiver acknowledges that the message has been received properly. In ATC, where fast decisions are needed and where situations can unfold rapidly, to only rely on *closed-loop communication* might actually hinder the effectiveness. Implicit communication is here proposed to ease the communication between the operator and the automation and opening up more time for planning or strategic decisions for the operator. Implicit communication might even be a peripheral activity by the operator which demands a rather low cognitive load.

6.4.1. Implicit communication as a teamwork factor

Within this scope of this dissertation, it is suggested to include implicit communication in *closed-loop communication* (see Figure 9, A) as a teamwork factor in the domain of ATC, to get the *what* (communication) but also a suggestion of *how* (implicitly). Implicit communication can affect efficiency, whereas *closed-loop communication* might affect safety by acknowledging that the correct message was delivered. With this approach, the ATCO could save time, which could be used for planning or strategic procedures instead.

Implicit communication could be applicable in all ATC environments where the operator and the ATM system need to communicate in an effective way. However, in current ATC environments, there is little support for implicit communication, and then only for human-human communication. For example in en-route, the Executive and the Planner can point at each other's screens to notify the other team member about something of interest. The act of pointing might be explicit communication. However, the results of it can lead to new knowledge for the receiver that might not be obvious only due to the pointing itself. Automatically transferring relevant information on the screen between the operators (instead of pointing) for a certain purpose or situation for the team member to notice could be a way of implicit communication instead. Thus, implementing support for implicit communication in ATC could open up time for planning and tactical procedures instead of having a system that forces the operator to double-check the information (as were the cases in Paper III and Paper IV). This will be illustrated in Example A, a result from the study in Paper III.

Example A

> Valuable time was spent on communication and interaction with the ATM system and pilots due to the increased amount of information when controlling several airports at the same time, compared with one airport. The ATCO looked at the voice communication system several times during the recorded scenarios and

during different stages of the arrivals of the aircraft. A reason for looking at the radio so many times is due to the needed change of frequency in a multiple remote tower. For each aircraft calling, the ATCO need to locate from which airspace (or airport) the aircraft is calling and then switch to the correct frequency on the communication system. However, if that kind of communication between the ATCO and the system could be performed implicitly instead based on, for instance, work patterns of the ATCO gathered from eye-tracking or other sensors, valuable time could be used for other critical tasks instead (planning, tactical procedures etc.) the ATCO has to perform. The frequency could be changed by the automation to the required one if the automation was designed to know which airport the ATCO is looking at. This could lead to work efficiency since the ATCO does not have to find information and communicate it on his/her own. However, an important design challenge is that if the communication between the automation and the ATCO changes, the work patterns will change as well and, thus, the support from the automation.

6.4.2. Work patterns to extract information

How to work with communication frequencies in digital or remote towers is an important research topic (Wittbrodt, Gross, & Thüring, 2010; Reynal et al., 2019). For example, if there will be one frequency for all the airspaces the tower ATCO is controlling or if there will be one for each airspace. However, there are many messages that need to be communicated between the technical system and the operator during a work shift. If implicit communication could be used, time might be saved that could be used for planning or other tasks instead. In addition, without explicit communication with the automation, one output source of the ATCO is free, which might decrease (or regulate) workload since the ATCO no longer has to, for instance, type in information or double-check information. However, one challenge of implementing support for implicit communication is that the automation and the operator need to be able to transmit and receive the communication. Since implicitly means nonverbal communication, other communication tools are necessary. One topic for further research, and as proposed in Paper III, is the use of work patterns.

Work patterns of the operator can be of use for the automation to provide the operator with situation-based information. For example, which airspace or airport the ATCO is working with could be accessible for the automation. Based on that information, the automation could change the frequency for the ATCO and implicitly communicating this back to the ATCO. A way of extracting work patterns from the operator is to use eye-tracking. The automation can use the knowledge of the operator's gaze as a source for communication. However, eye-tracking attached to the operator can be intrusive on the operator work (see Section 4.2). Therefore, standalone equipment is necessary to not jeopardise safety. Another way of extracting work patterns is through speech recognition or recordings of head and body movements. It is assumed that the clearest patterns are extracted from a combination of several behavioural recordings. However, how to design automation to support implicit communication without interfering with safety needs to be further explored.

6.4.3. Implicit communication in relation to other teamwork factors

Implicit communication, just like *closed-loop communication*, can assist to build *mutual performance monitoring* (see Figure 9, B) (Rognin & Blanquart, 2001) by communicating to the other team members of what the current task is or provide information about the current situation (Christoffersen & Woods, 2002). Implicit communication is assumed to be a faster way of communicating during stressful situations to maintain *mutual performance monitoring* (Salas et al., 2008). In the study for Paper I, some ATCOs used only a thumb up in some situations to communicate the current status to the team members, contributing to *mutual performance monitoring* through implicit communication. Having knowledge about the other team members could support implicit communication since the knowledge itself might be necessary enough in some situations. In a study by Breazeal et al. (2005), implicit communication and behaviour were used as cues to understand the robot the humans where interacting with, similar to *mutual performance monitoring*. Having *mutual performance monitoring* and implicit communication could also lead to *backup behaviour* since the operators could, through implicit means, communicate to the team members how the situation is unfolding and, consequently, if backup is required. In addition, *shared mental models* could also support implicit communication (see Figure 9, C) due to the common ground of work procedures and goals, something that becomes even more important during stressful conditions. The amount of communication often decreases between the team members during stress and, therefore, forcing the team to rely more on implicit communication than on explicit communication as well as on *shared mental models* (Kleinman & Serfaty, 1989; Salas et al., 2005).

When designing automated systems, behavioural analysis like the one conducted in Paper III or as in the work of Eggeling et al. (2015) can be used to predict operator actions. However, having efficient communication between humans also implies that humans have knowledge about each other, what they are doing or for example of what they can or cannot do in certain situations. Having such knowledge eases and makes communication more efficient since less time has to be spent on explanations. It should be the same when working with automation. In order to have efficient communication with automation, the human operator should know what the automation can or cannot manage to be able to have as efficient communication as possible. The human operator should have knowledge about the boundaries of the automation.

6.5. Boundary awareness

Even though automation to some extent already is implemented in several domains (for example conflict detection tools in ATC), unpredicted situations or stressful situations might still occur and the operator needs to have situation awareness to be aware of unfolding events (Mica R. Endsley, 1995, 1996, 2015; Lundberg, 2015; N. A. Stanton et al., 2017). The more automation is implemented in different domains, the more it will be invisible, and the easier it will be for humans to see it as irreplaceable. Humans become addicted to technology (Kakabadse, Porter, & Vance, 2007), which implies that humans also push the responsibility away and blames the technology when something goes wrong. In addition, if the operator does not understand and does not know what the automation is doing, there are risks for automation surprise (N. Sarter et al., 1997; Baxter et al., 2012; Bradshaw et al., 2013; Strauch, 2017). It is suggested to support the development of operator mental models when working with learning systems that might have inconsistent behaviours (Mica R Endsley, 2017). However, with the introduction of automation comes also the necessity to have not only awareness about the situation and environment, but also about the automation, especially if it is seen as a team member. Therefore, it is proposed within the scope of this dissertation (Paper IV) that knowing the functions of the automation, the boundaries of what the automation is capable of, and to know the consequences of the automation are prerequisites to implement higher levels of automation in high stakes environments such as ATC. This goes in line with the automation interface that Mica R Endsley (2017) proposed as well. Therefore, the concept of boundary awareness is proposed (Paper IV) as a teamwork aspect. Boundary awareness is defined as *awareness of the boundary conditions of the automation and the dynamic automation performance envelope*. Automation performance envelope refers to the automation performance and the effects of the current situation on the automation.

6.5.1. The notion of boundary awareness

Boundary awareness is necessary for the operator to know what the automation can or cannot manage, to keep the operator in the control loop, and, hence, to avoid or at least decrease automation surprise. The hard part is not always to learn how to use automation, but to know how to not use it. Using it in the wrong way can lead to confusion and that the automation ends up outside of its boundaries. Boundary awareness contributes to the operator's knowledge about the automation and what would happen if it goes out of boundaries. Figure 10 illustrates how boundary awareness is related to situation awareness, mode awareness, mental models, device models, and external factors such as situational conditions (traffic movements, weather, etc.).

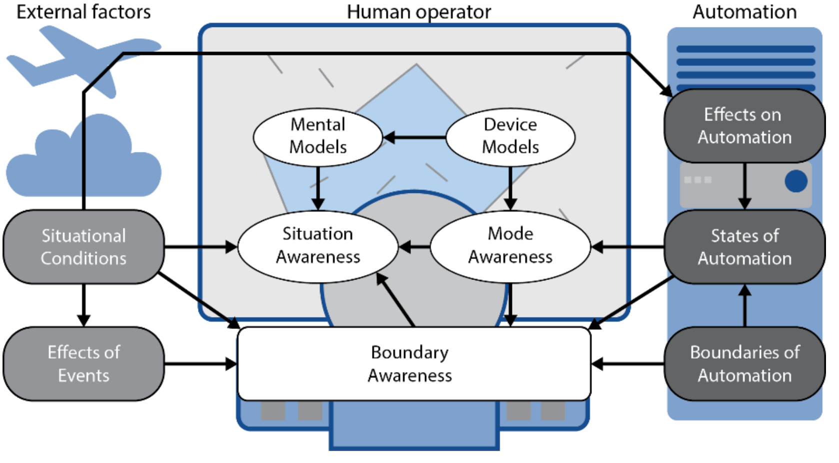

Figure 10. In order to build and maintain boundary awareness regarding automation, the operator needs information about the situational conditions, the automation performance envelope, of the mode of the automation. Figure from Paper IV.

Situation awareness (Mica R. Endsley, 1995) concerns "knowing what goes on" regardless of automation is involved or not. Boundary awareness, however, concerns dynamic situations that involve human-automation interaction. Thus, it becomes increasingly necessary as automation is implemented. The distinction between boundary awareness and situation awareness can be further explained when considering automation degradation. During automation degradation, boundary awareness is needed to understand and predict how the automation will affect the work situation for the operator. Boundary awareness could provide the operator with knowledge about what the automation can manage in the situation at hand and, hence, assist the operator to plan and predict upcoming situations. Still, situation awareness is needed to be able to take over tasks from the automation, if it fails. However, an operator having boundary awareness of the automation may be able to anticipate automation degradation and, hence, avoid automation surprise through appropriate action. An example of when boundary awareness is of use is illustrated with an example from Paper IV.

Example B

A new automation was introduced for ATCOs to assist the ATCO in arrival sequencing (Rydell et al., 2015). The automation provided the ATCO with a time of when the aircraft was supposed to reach a certain point in the airspace. However, there were uncertainties for how the automation was actually working. The ATCO gave clearance to the aircraft to turn left for sequencing purposes and after a short while instructed the pilot to activate the automation to continue on the original route. The pilot confirmed the reroute and the instruction to establish the automation if possible. However, the ATCO noticed that the aircraft was still travelling north instead of turning back to its original route. Therefore, the ATCO asked the pilot to resume navigation towards the TMA and retain the solution proposed by the automation. The pilot confirmed this. Thus, both the ATCO and the pilot believed that using the automation was possible in this case. Otherwise, the ATCO would not have cleared it, nor the pilot confirmed it. However, after a couple of seconds, the pilot informed the ATCO that the aircraft would be unable to use the proposal from the automation. Thus, the ATCO instructed the pilot to cancel the automation altogether. This example illustrates that it is clear that the ATCO and the pilot were uncertain about the ability of the automation. Therefore, it is proposed that the ATCO need to have boundary awareness to know what the automation can or cannot handle and what happens when the automation goes outside of its boundaries. In the case from Paper IV, the ATCO ends up with more work due to a lack of boundary awareness, compared to when there was no automation at all assisting the ATCO.

6.5.2. Boundary awareness in relation to other teamwork factors

Boundary awareness can be related to some of the human-human teamwork factors from the Big Five model (Salas et al., 2005). For example, in human-human teamwork, it is important to have *mutual performance monitoring* and to know that the team members are capable of upcoming situations. This is of particular importance in stressful situations (Paper I) to know how the team members are coping with the situation at hand. *Mutual performance monitoring* might also improve efficiency (Salas et al., 2005), a prerequisite in ATC today to cope with the increasing demands. Boundary awareness affects *mutual performance monitoring* (see Figure 9, D). It is central for the team members, even though one team member is an automation, to know that everyone can cope with and manage the situation at hand. In order to be able to achieve this knowledge, boundary awareness might be one solution. If the human operator could gain boundary awareness of the automation, the operator would know what the automation can or cannot manage and what it is doing (*mutual performance monitoring*), and hence, plan for the kind of teamwork and work strategies which are necessary. Designing for *mutual performance monitoring* could also assist in building boundary awareness (see Figure 9, D). If the operator has knowledge of the team members' work and status, through for example shared situation based information, it can assist the operator in knowing the development of the situation, and, hence, if the situational conditions will affect the automation (see Figure 10).

In addition, *adaptability* is important for human-human teamwork (Paper I and Paper II). Due to the rapid, and sometimes unpredictable, changes during ATC work, being able to change plans is of great necessity. It is also important to know the consequences of the changes and the actions in such high stakes environments. The same goes for automation. Since automation is introduced due to the increasing traffic flows and the increasing demands, and since the ATCOs have stated that they want to stay in control (Paper II), it is important that the automation is flexible to adapt to the changes. Having boundary awareness might affect *backup behaviour* and *adaptability* (see Figure 9, E and F) since the ATCO would know the boundaries of the automation and how it would manage different situations that arise and hence plan for it.

Boundary awareness can, thus, support and strengthen teamwork, which in turn can reduce automation surprise and, hence, increase safety. Therefore, it is proposed that boundary awareness can be seen as a supporting teamwork aspect and something that should be further explored within design research of how to design automation that enables boundary awareness.

6.6. Future research

The previous discussion sections have already proposed some topics for future research. However, this section will extend some of those ideas but also propose some further topics that are of relevance for continues (design) research within human-automation teamwork.

It seems that the control room industry, and in particular the ATM industry, has some challenges when it comes to implementing automation based on the findings from the work within the scope of this dissertation. The general idea with automation within ATM is not, at the moment, to replace the human operator with automation. Instead, automation is supposed to support the operator. Research has regarded these topics previously and concluded that having a human operator to monitor the automation process is not efficient. Still, operators have a fear of automation taking control from the operator and leaving the operator to monitor the automation and being a backup system to the automation (Paper II). This needs to be further addressed and explored to decrease the scepticism towards automation and decrease automation surprises, to increase teamwork.

Research is needed regarding what would happen if the fear of automation continues. It would be of interest to explore how that would affect the work with the automation and the operator's workload. In turn, how the fear of automation would affect safety, especially in ATM with its outstanding safety record, is of particular importance to investigate. Moreover, it would also be of interest to explore what would happen if the ATCOs' predictions are correct. Meaning that the roles of the automation and the ATCO changes, making the ATCO a backup system to the automation.

As shown within the work of this dissertation, the human operator and the automation should work as a team where the operator maintains in the loop of control. This has also been shown in previous work (Christoffersen & Woods, 2002; Glen Klein et al., 2004; Bradshaw et al., 2013; Mica R Endsley, 2017). This is of particular importance as long as the human operator has legal responsibility. Even though there is already research regarding the operators' involvement in the control process, more research is needed of how involved the operators actually need to be in the decision making, having active control, and execution processes to maintain situation awareness while having the legal responsibility. It can be assumed that the operator would still need a lot of information about the traffic movements, the automation, and the overall situation, even though the operator would work as a backup system to the automation. This is a central design challenge.

Previous research has explored role allocation. However, research is also needed regarding designs where the responsibility and boundaries between automation and operator could be more indistinct or flexible. In addition, it is important to further explore how the operator wants to work with the automation, for example, whether the operator wants a flexible system.

In addition to the human factors design perspective, ergonomics perspective needs to be designed for as well. The physical work station, including artefacts, computers, automation or any other tool the operators are using in their work, affects not only the work of the operator; it affects the teamwork, the communication between team members, and situation awareness. Therefore, implementing automation requires research of how new designs of automation affects these elements as well.

More research regarding teamwork and how automation can become a team member is also needed. ATM has been the case domain for the work within the scope of this dissertation. However, the teamwork factors found here could be just as important in other domains. For example, fighter pilots ranked *mutual performance monitoring* as the most important teamwork factor, followed by *closed-loop communication,* and *shared mental models* (Ohlander et al., 2016). In contrast, the findings within the scope of this dissertation have shown that operators in ATC believed that *adaptability*, *mutual performance monitoring, shared mental models*, and *mutual trust* are important teamwork factors. However, it would be of interest to explore if similar control room domains would get similar results.

Even though the teamwork factors explored within the scope of this dissertation are a good start towards designing automation, more information is needed in how (and why) automation can be designed in regard to these teamwork factors for the human operator to experience efficient teamwork. For example, design research could explore if the automation must have the quality of all of these teamwork factors for the operator to have satisfying teamwork with the automation. Design research could also address if the teamwork, and the necessary teamwork factors, would differ between different levels of automation. For example, some teamwork factors might be more important when working with higher levels of automation compared to lower levels of automation.

Within the scope of this dissertation, the teamwork factors *mutual trust* and *team orientation* has only been briefly touched upon. However, even though trust in automation is a common research topic, it should be further considered how to design for trust in human-automation teamwork. It would be interesting to explore if the necessary levels of trust differ between human-human teamwork and human-automation teamwork, as within the work of Madhavan and Wiegmann (2007), especially in ATC and compare this to other control system domains. Trust allows for smooth flow of communication between humans and non-humans in teams, which is prerequisite for the function of complex systems such as ATC. Therefore, design research should continue to focus on how to design automation that supports trust between human operators and automation. Moreover, team orientation was seen as a prerequisite for teamwork in ATC. It would be interesting to explore how this teamwork factor manifests in control system domains and if it is just as relevant for human-automation teamwork as for human-human teamwork. Both qualitative and quantitative studies are suggested to be conducted to understand the operators' view on this teamwork factor, as well as how it is actually manifesting when working in close collaboration with automation.

Driven from human factors, this dissertation has provided two new teamwork aspects that could enhance human-automation teamwork: implicit communication and boundary awareness. However, these aspects are not design guidelines. There are no means to support them yet. Thus, more design research regarding implicit communication and boundary awareness is necessary.

Already twenty years ago, it was proposed to further explore how the automation or the technical system helps or not with implicit coordination between operators (Bressolle, Benhacene, Boudes, & Parise, 2000). However, implicit communication and the support for it is still highly relevant. Thus, investigating how much implicit communication affects the work of the operator (compared to explicit communication and *closed-loop communication*) is also needed. In addition, how it affects other teamwork factors, situation awareness, and team situation awareness during operations is important to understand to be able to design for it. Since one proposal within the scope of this dissertation is to use visual scan patterns and work patterns of the operator for implicit communication with the automation, there needs to be further design research regarding how the design of new functions and tools affects the work of the operator, and hence, the work patterns that the automation is using. Changing the tools and functions the operator is working with will change the work patterns. In addition, there is a requirement for the automation to understand the purpose and meaning of the operator's visual activity. C. Westin, Vrotsou, Vitoria, Lundberg, and Meyer (2019) used an approach to try to formalise "best practice" scan patterns in relation to specific tasks and situations. The automation could then monitor the controller and verify or probe expected visual activities. However, more research is needed regarding work patterns and the operators' visual activities to be able to use it for communication.

The degree to which boundary awareness affects teamwork between the operator and the automation should be further investigated. It is assumed that automation surprise would decrease when having knowledge about the automation and its boundaries. However, design research should continue regarding to what extent the operator should have knowledge about the automation (C. A. Westin et al., 2019) without encounter information overload for the operator or the need to have extremely long training sessions. It is assumed that boundary awareness affects *mutual performance monitoring, backup behaviour, shared mental models*, and also *mutual trust* due to the knowledge about the capability of the other team members. However, research is needed regarding to what extent boundary awareness affects the teamwork factors and, thus, team performance.

7. CONCLUSIONS

The aim of the work within the scope of this dissertation has been to explore human-human and human-automation collaboration in ATC from a human factors design point of view. Supporting cognitive ATC work when automation is increasing is needed to meet the increased demands on productivity while maintaining high safety. The results from the work within the scope of this dissertation indicate that *mutual trust*, *adaptability*, *shared mental models*, and *mutual performance monitoring* were the top-ranked teamwork factors in ATC for both human-human teamwork and for human-automation teamwork. However, the rankings of the teamwork factors differ between ATC environments. In addition, teamwork is important during both stressful work, during abnormal situations, and during routine operations. This is due to the increased need for coordination and information acquisition during such situations. Hence, when automation is implemented, it should support teamwork in all kind of situations and not only work during routine operations. Even though teamwork between operator and automation is important in ATC, there is a fear among operators that automation will take control from the operator. In addition, operators fear to end up in a role of monitoring the automation and being a backup system to the automation, instead of automation being the backup system to the operator as today.

Within the work of this dissertation, two new possibilities to strengthen human-automation teamwork has been identified: implicit communication and boundary awareness. It is proposed that implicit communication should be a part of the teamwork factor *closed-loop communication* and that it could be supported by *shared mental models*. A suggestion is to use the work patterns of the operator through eye-trackers for the operator and the automation to implicitly communicate. Boundary awareness is the operator's knowledge about the boundaries the automation might have. Having boundary awareness can assist the operator to foresee situations regarding the automation and hence, strengthen the teamwork between the operator and the automation.

The results found within the scope of this dissertation might assist in further exploration of possibilities within the human-automation teamwork topic. Based on these results, it is proposed to design automation to support several teamwork factors between the automation and the human operator, but especially to design for implicit communication and boundary awareness. Implicit communication and boundary awareness can be used to aid system designers and developers in creating automation, and hence, enhance human-automation teamwork. Good teamwork can enhance performance and support of maintaining safety (through efficient coordination and communication), which are two of the major reasons for introducing automation in the first place. The findings from the work within the scope of this dissertation can create a solid foundation for further design research within the topic of human-automation teamwork regarding boundaries of the automation and the communication flow between human operators and automation.

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