Identification of Complexity Factors for Remote Towers

Billy Josefsson
Air Navigation Services of Sweden (LFV)
Research & Innovation
Norrköping, Sweden
firstname.lastname@lfv.se

Joern Jakobi
and Anne Papenfuss
Institute of Flight Guidance
German Aerospace Center (DLR)
Braunschweig, Germany
firstname.lastname@dlr.de

Tatiana Polishchuk
Christiane Schmidt and Leonid Sedov
Communications and Transport
Systems, Linköping University
Norrköping, Sweden
firstname.lastname@liu.se

Abstract—**An implementation of the Remote Tower concept comes with the challenge of optimizing staff resources subject to safety requirements. To distinguish safe from unsafe assignments, the quantification of tower controller workload—which is not a new problem—needs to be reconsidered in the setting of a remote tower environment. We plan to identify the remote operation specific complexity factors, which will be the basis of finding measures that have a high correlation to these factors that together describe the workload. In this paper, we analyze simulation data for these complexity factors. In the simulation different controllers rated the workload while monitoring multiple airports (either with simultaneously visible screens, or switching between the displays). We focus on complexity factors that stem from the interplay of Tower and Ground Control. The resulting list of the most significant complexity factors gives a base for our future quantification of remote tower controller workload.**

Keywords—**Keywords-Remote Tower Services; Workload; Taskload; Complexity Indicators; Human Performance**

I. INTRODUCTION

Remote Tower Services (RTSs) allow that various airports are controlled by air traffic controllers (ATCOs) located in a Remote Tower Centre (RTC). The concept was designed to counter staff-demand imbalances, which often appear at small airports (with about 30-120 movements a day), and lower their operational and human-resource (HR) costs. This new concept fundamentally changes how operators provide Air Traffic Services, as it becomes possible to control several airports from a single controller working position. In such settings an ATCO works at a so-called “multiple position” at the RTC, which means that he/she can handle two or more airports from one Remote Tower Module (RTM).

When a larger number of airports should be controlled from a RTC, ATC procedures need to ensure that none of the ATCOs is confronted with traffic-inherent, non-manageable situations, that is, with situations in which the ATCO cannot guarantee safe operation by controlling the traffic s/he is in charge of. The problem is of increased interest to the Remote Tower management, as they attempt to create reasonable rosters for Remote Tower ATCOs. The problem of optimizing rosters for air traffic controllers in RTC was first considered in [8]. The authors used the number of Instrumental Flight Rules (IFR) flights as a measure of staff workload. But according to LFV (Swedish Air Navigation Service Provider) traffic patterns, IFR traffic accounts for only 40% of the workload at smaller airports, and other important aspects, which contribute to staff workload, such as ground traffic movements, bad weather conditions, seasonal variations, Visual Flight Rules (VFR), and extra traffic movements should be taken into account.

Quantification of controller workload becomes even more critical in the context of “multiple” Remote Control. Here the task is not only to assign controllers to a RTM providing control to one or more aerodromes, such that various safety and operational requirements are fulfilled, but, in particular, it is important to ensure that no ATCO is assigned to control aerodromes that together constitute a non-manageable workload. To prevent such situations, RTC management may, e.g., employ two ATCOs during a potential risky period for one RTM controlling two airports that otherwise is assigned to a single ATCO. But how do they decide in which situations extra staff is needed? In general, we can say that we want to split a position if the workload becomes too high for a single ATCO to handle. An objective assessment of workload and airspace capacity (complexity) is crucial in order to find an appropriate level of human responsibility. This is important as the current method of evaluating workload and complexity in air traffic can be seen as imprecise, subjective, or both.

While a lot of experiments and quantitative evaluations exist for en-route traffic, this is not well researched for aerodrome control, and even less so for remote tower control. Remote Towers further highlight a gap in assessing controller workload: various factors influence the mental workload of an ATCO, and there has been relatively little research into all these factors. Thus, a better understanding of workload in general—but even more so of the situation with remotely controlled airports—is vitally important. Hence, before we can make any quantitative statements (and define—hard or soft—thresholds), we aim to identify factors that potentially drive the complexity of the traffic situation the RTC ATCO has to handle. The responsibilities of an RTC ATCO will include not only runway control, but also ground control, ground support and sometimes even apron control. We are, in particular, interested to identify complex situations that derive from the interaction of different controller tasks. Exactly these situations will be what distinguishes a workload description of a traditional tower controller from that of a RTC ATCO.

With this paper we do not aim to give an exhaustive list of possible complexity factors for RTCs, but we present a first subset of these factors. We focus on complexity factors that stem from the interplay of Tower and Ground Control. For that we analyze the data from [19], which DLR kindly made available to us, described in detail in Section II.

A. Related Work

For en-route traffic, various assessment forms of workload have been considered [2], [4], [6], [9], [13], [20]. Two often used methods can be distinguished by the study goal: studies with a HR-based perspective often use different scales (for example adapted Cooper-Harper scale, e.g. [13], [16], [19]) ranging from „no problems“ to „traffic situation is not controllable“. Then controllers are asked to rate the last handled traffic situation frequently during a simulation run.

Another approach tries to identify certain factors that drive the complexity of an airspace and aim to find an observable measure (e.g., eye-movements, clicks on the radar screen etc.) that has a high correlation with the aggregated complexity factors. Many ATC complexity indicators have been proposed in the literature [7], [9], [14], [22].

Several models were proposed aiming at relating ATC complexity to workload. For example, taskload models [5], [21] compute the cumulative time required to execute control tasks. Linear regression models such as the popular dynamic density models [10], [16], [22] approximate subjective workload ratings by a linear combination of a number of ATC complexity measures. Other works use a neural network instead of a linear model [1], [6] to approximate subjective ratings.

There are two significant studies, which attempted to assess complexity in the tower environment. Netjasov et al. [18] developed a generic metric for measuring the complexity of the terminal airspace (TMA). The work classified and quantified the complexity factors within the TMA, dividing them into static and dynamic components. In [12] the authors investigated factors that contribute to complexity and their incidence within Federal Aviation Administration Air Traffic Control Towers (ATCTs). Sixty-two Air Traffic Control Specialists (ATCSs) from six ATCTs rated 29 complexity factors from local and ground controller perspective. The relative contribution of each of the complexity factors was analyzed and extended with the corresponding strategies which tower controllers use to mitigate complexity in [11] .

While these works create a good base for understanding situations with high controllers' workload, they do not cover the correlation between the discovered complexity indicators and the resulting workload explicitly.

In [15], [16], [17] various aspects of work organization and human performance issues related to the remote operation are considered. The authors tested several methods to control two airports from a single RTM. The aim of the studies was not to propose a specific operational concept but to vary influencing factors in order to understand their impact on controller workload, situational awareness and performance. Using human-in-the-loop simulations they analyzed how the system design may influence behavioral strategies and thus controller performance, and suggested several ideas on the design of novel RTM workplaces. These works provide a basis for our current paper.

ATCOs permanently survey air traffic, anticipate and detect (potential) conflicts, intervene to resolve them, communicate with pilots and ATCOs of neighboring sectors for handover, and perform various other tasks that contribute to the task complexity and drive an ATCO's mental workload. Both workload and taskload reflect the demand of the air traffic controller's control task: the taskload measures the objective demands, while the workload reflects the subjective demand experienced during that task. Of course, any quantitative, general model, will access taskload rather than workload, however, the factors that we extract influence both, taskload and workload, and we will use workload throughout the rest of this paper.

Roadmap. In Section II we detail how the data was collected and what was recorded. We present the data analysis in Section III and conclude the paper in Section IV.

II. DATA

The simulation setup by DLR (see [17], [19]), used working positions that could be used to either have one ATCO working at two airports, or a team of two controllers working at the two airports together. Six teams of ATCO pairs were used for the simulation runs. After an introduction, each ATCO participated in two training runs, and the final simulation. The two airports simulated were Erfurt and Braunschweig.

The study was designed to compare three different approaches to work distribution:

(a) One controller responsible for a single airport
(b) Two controllers responsible for both airports (controller and coordinator)
(c) One controller responsible for both airports

All simulation scenarios had "high" traffic volume to achieve parallel movements at Erfurt and Braunschweig. In some simulation runs both airports were visible simultaneously, in other runs, a switching of the screen was necessary to see the other airport. In this paper, we will focus on (c).

A. Data Collection

An adapted Cooper-Harper Scale (see the appendix of the thesis by Peters [19] for the complete scale) builds the base for the data collection—it is an adaptation of an already altered Cooper-Harper Scale that combines handling-qualities and workload to the ATC environment. The scale uses a rating from 1-10 to differentiate the impact of traffic situations on perceived handling qualities, shown in Table I. This scale was also used to assess the influence of workplace design on ATCOs workload. A rating of seven or higher was handled as being critical in terms of safety. Whilst one ATCO was controlling the traffic, the other observed the situation and was asked to assess any multiple specific situation with the adapted scale. There was a set of pre-defined situations, like

TABLE I
SUMMARY OF THE ADAPTED COOPER-HARPER SCALE BY DLR

Rating	Evaluation	Question for Evaluation
1	No problems, desirable	Is the situation solvable without major Disturbance?
2	Simple, desirable	
3	Adequate, desirable	
4	Small, but disruptive "delays"	Is the situation solvable by capacity-reducing measures?
5	Medium loss of capacity, which can be improved	
6	Very disruptive,	
	but tolerable difficulties	
7	Problems to predict development of traffic situation	Is the situation solvable if the ATCO works with a reduced situational awareness?
8	Problems in information processing	
9 9	Problems in information reception	
10	Impossible	

two simultaneous landings. Additionally, the observer ATCO was asked to rate any situation which could only occur because of the multiple working conditions.

B. Data Set

The data set consists of 222 ratings for 222 situations, produced by 12 different ATCOs. On average, an ATCO rated 19 situations (sd = 8), see [17] how the simulation was prepared. Each rating consists of the following information:

- Team number
- Experimental condition, training or not
- Workplace design; Switching necessary (UJ) or not (UN)
- Predefined situation number (one out of a list of nine, e.g., landing at one airport and taxiing traffic at the other)
- Evaluation according to the adapted Cooper-Harper Scale
- A brief description of the problem/situation

Situations were part of a larger 20 minute simulation scenario. Every relevant pre-defined situation in the simulation was a "pair" of movements or actions happening at two airports at the same time.

Data preparation for the analysis consisted of a coding of the ratings based on the predefined situations and the problem description. Coding variables were created and adapted during the coding process to capture all ratings. Besides typical flight phases and connected ATCO clearances (e.g. initial call, landing, called events), conflicts, emergencies and performance problems of the ATCO (e.g. mix-up of airports) were used for coding. Finally, the coding scheme consisted of 23 variables. These variables are the initial events.

III. IDENTIFICATION OF CRITICAL FACTORS

We aim to identify the critical complexity factors that drive the workload of a remote tower ATCO. To this end, we want to identify the situations at the two controlled airports in the simulation that induce a risk. We chose to analyze the data by aggregating the information w.r.t. combination of events. Combinations of events build a situation, that is, we, for example, identified all controllers that evaluated a scenario in which the two events taxi and landing appear. In the beginning, we focused on pairs of events (see Section III-A), and finally considered triples of events (see Section III-B). In addition, we filtered out consequences of (simultaneous) events at two airports, and analyzed which events resulted in these problematic consequences (see Section III-C).

A. Pairs of Events

We classified the situations, defined by pairs of events by two criteria: by the average (mean) controller rating, and by the maximum controller rating. In both cases we separated the analysis for the two different workplace designs with switching of the video panorama between airports ("UJ") and the set-up where both airports were visible to the ATCO at all time ("UN"). 65 different situations described by pairs of events where identified within the data in the condition "UN", 55 in condition "UJ". A comparison of the two workplace designs is given. So, the effect of having all relevant information visible at all time on perceived handling qualities can be estimated.

1) Mean Controller Rating: The rationale behind using the mean controller rating is that a situation can be manageable or unmanageable depending on the ATCO's experience, age, and various other factors. If we aim to achieve a generic measure, we can assume an "average controller". We are particularly interested in the factors that will be problematic to this average controller. Hence, we computed the mean over all ATCO evaluations for the situation as an approximate to this average controller. The list of all event pairs with their according mean rating is shown in Figure 1 and Figure 2 for the UJ and UN setup, resp.. We identify all event pairs with a mean controller rating of at least 7 (shown as red bars and red pairs in Figure 1 and Figure 2, respectively) as critical: the average controller needs to operate at least with reduced situational awareness, or even deems the situation impossible to handle. We identify 18 critical event pairs for the UJ and 17 for the UN setup.

We observe that the lists of critical event pairs differ slightly, however, pairs with a conflict at a single airport are prevalent in both lists (highlighted in green in Table II), while, for example, pairs that contain an emergency are problematic for the average controller in the UJ setup, but not for the average controller in the UN setup (highlighted in purple in Table II).

2) Maximum Controller Rating: Using a maximum controller as the representative instead of the average controller rating could be considered as more conservative: Possibly, only a single ATCO observer experienced the criticallity associated with a certain situation as very high (assigns a 7-10 to the situation), and all other ATCOs deem it solvable. However, first of all we like to identify all critical factors for the remote tower environment. Extending the list that we might have to filter out by actual correlation later on, anyhow is the approach by which failing to identify an important factor is less likely. Moreover, if we come back to our long-term application goal of such a complexity measure: if we want to ensure safe operation, we should exclude situations that will be unmanageable for any ATCO, hence, integrating all these factors is our aim in the second set of factors.

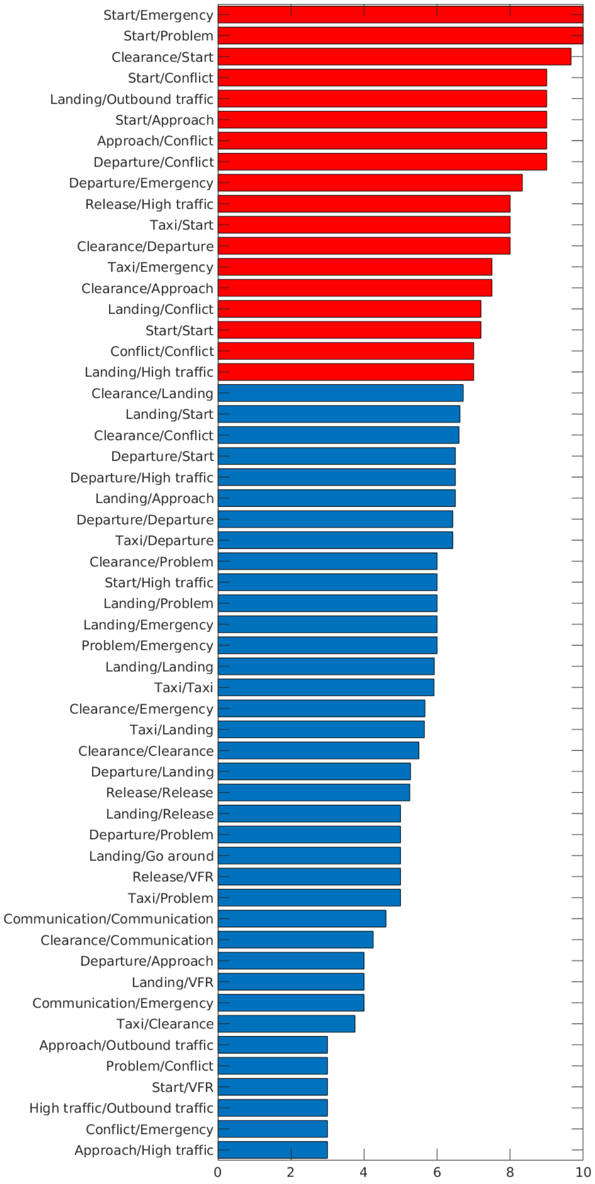


Fig. 1. Event pairs for the UJ setup ordered by mean controller rating, red bars indicate a mean controller rating of at least 7.

The list of all event pairs with their according maximum rating is shown in Figure 3 for the UJ setup and in Figure 4 for the UN setup. Obviously, the number of situations with a maximum rating of at least 7 is at least as high as the number of event pairs with a mean controller rating of at least 7. The ratio of event pairs that are deemed critical to the total number of event pairs is considerably higher for the UJ setup (38/55) than for the UN setup (31/65). Also the number of event pairs that obtain a maximum rating of 10 (part of an impossible situation) is more than four times as large for the UJ setup (22 pairs) than for the UN setup (5 pairs). Only 9 out of these 22 event pairs are considered critical at all for the UN setup.

If we consider the event pairs that are rated critical for the UN, but not for the UJ setup, we observe the following pairs:

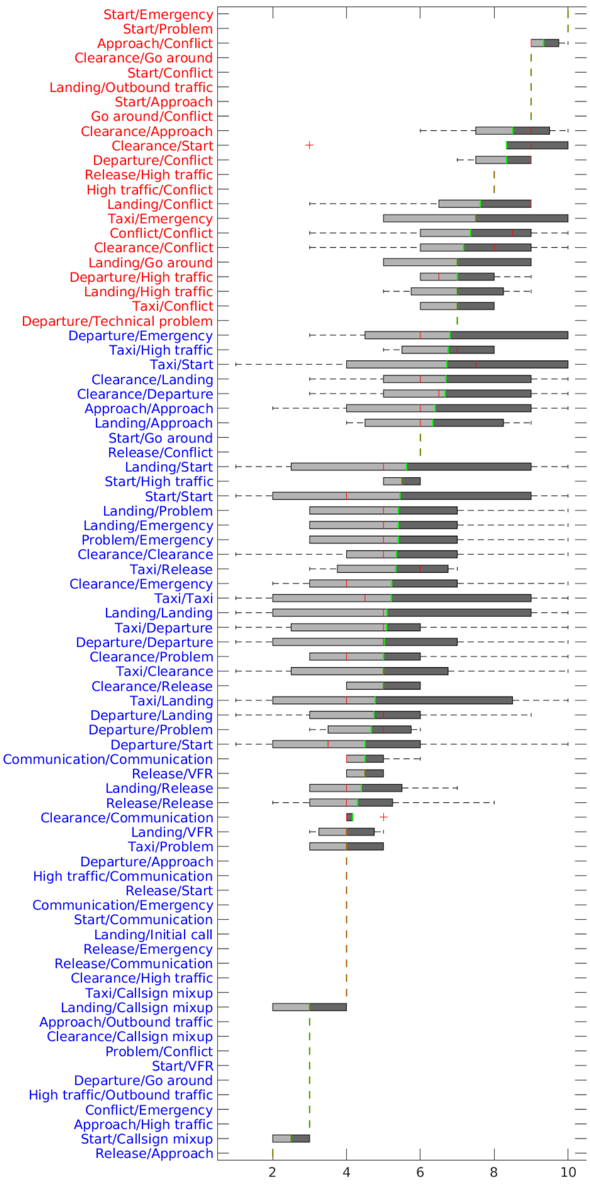


Fig. 2. Boxplot of the controller rating for the event pairs for the UN setup ordered by mean controller rating, ties are broken by ordering w.r.t the maximum. The mean is shown in green, the median in red (if they coincide, only the mean is shown). Event pairs colored red indicate a mean controller rating of at least 7.

Approach and approach, taxi and clearance, go-around and conflict at a single airport, clearance and go-around, landing and go-around, taxi and high traffic volume, high traffic volume and conflict at a single airport, taxi and conflict at a single airport, departure and technical problem, landing and release, and taxi and release.

The following event pairs are rated as critical for the UJ setup, but not for the UN setup: problem and emergency, clearance and problem, taxi and start, clearance and emergency, start and emergency, taxi and departure, landing and emergency, taxi and taxi, landing and problem, departure and emergency, departure and start, start and problem, taxi and emergency, conflict at a single airport and conflict at a single airport, landing and outbound traffic, landing and approach, and release and high traffic volume. Again, we can observe

TABLE II

EVENT PAIRS THAT WERE CRITICAL FOR THE MEAN CONTROLLER RATING FOR EITHER THE UN OR THE UJ SETUP. EVENT PAIRS THAT WERE NOT CRITICAL FOR A SETUP ARE DENOTED BY AN ‘’-”, THE OTHER EVENT PAIRS ARE SHOWN WITH THEIR MEAN CONTROLLER RATING

Situation	UN	UJ
Approach/Conflict	9.5	9.0
Clearance/Approach	9.5	7.5
Start/Conflict	9.0	9.0
Start/Approach	9.0	9.0
Landing/Go around	9.0	-
Clearance/Go around	9.0	-
Go around/Conflict	9.0	-
Landing/Conflict	8.33	7.2
Approach/Approach	8.0	-
High traffic/Conflict	8.0	-
Clearance/Conflict	7.57	-
Departure/High traffic	7.5	-
Clearance/Start	7.0	9.67
Departure/Conflict	7.0	9.0
Landing/High traffic	7.0	7.0
Departure/Technical problem	7.0	-
Taxi/Conflict	7.0	-
Start/Emergency	-	10.0
Start/Problem	-	10.0
Landing/Outbound traffic	-	9.0
Departure/Emergency	-	8.33
Taxi/Start	-	8.0
Release/High traffic	-	8.0
Clearance/Departure	-	8.0
Taxi/Emergency	-	7.5
Start/Start	-	7.2
Conflict/Conflict	-	7.0

TABLE III

TOTAL NUMBER OF EVENT PAIRS, AND SHARE OF CRITICAL EVENT PAIRS

	UN	UJ
# identified event pairs	65	55
# event pairs with mean rating$\geq$ 7	17	18
share of event pairs with mean rating $\geq$ 7	26%	33%
# event pairs with max rating $\geq$ 7	31	38
share of event pairs with max rating $\geq$ 7	48%	69%

that situations with an emergency at one airport have a higher problematic significance for the UJ setup.

In general, we can conclude that for the UJ setup a higher ratio of all event pairs leads to a critical rating, see Table III. This effect can be explained by the workplace design which prevented ATCOs to have all relevant information available at the same time. As this experimental condition was used for scientific purpose but not for operational use, the following analysis focusses on the UN setup—the setup that is also planned for the RTCs in Sweden.

For better comparison of the controller ratings w.r.t the mean and the maximum we give a boxplot for the UN setup in Fig. 2.

B. Triples of Events

While the analysis of pairs of events gives us an idea, which factors decrease handling qualities, they often receive a higher rating when they are part of a situation with even more events. Hence, we consider triples of events. In this subsection, we consider only the UN setup. In particular, we consider the triples of events for which the rating dominates at least the rating of one of its sub-pairs. For example, for a triple of events (A,B,C) we consider the event pairs (A,B), (B,C), and (A,C), and consider it as a complicating triple if the rating of the triple (A,B,C) dominates at least one pair, e.g., (A,B)—it could dominate w.r.t. the mean or maximum rating, that is, (A,B,C) could have a mean rating of 6 and maximum rating of 9, while (A,B) has a mean rating of 5 and a maximum rating of 10, or a mean rating of 7 and a maximum rating of 8. The idea is that in this case adding an event clearly increases the complexity of the situation for the ATCO (while for a triple that does not dominate any of its sub-pairs, the intrinsic complexity seems to already stem from a combination of two factors). Of course, such dominance is in particular interesting for those triples of events that have a rating of 7 or higher w.r.t. at least one criterion, which we consider as critical triples.

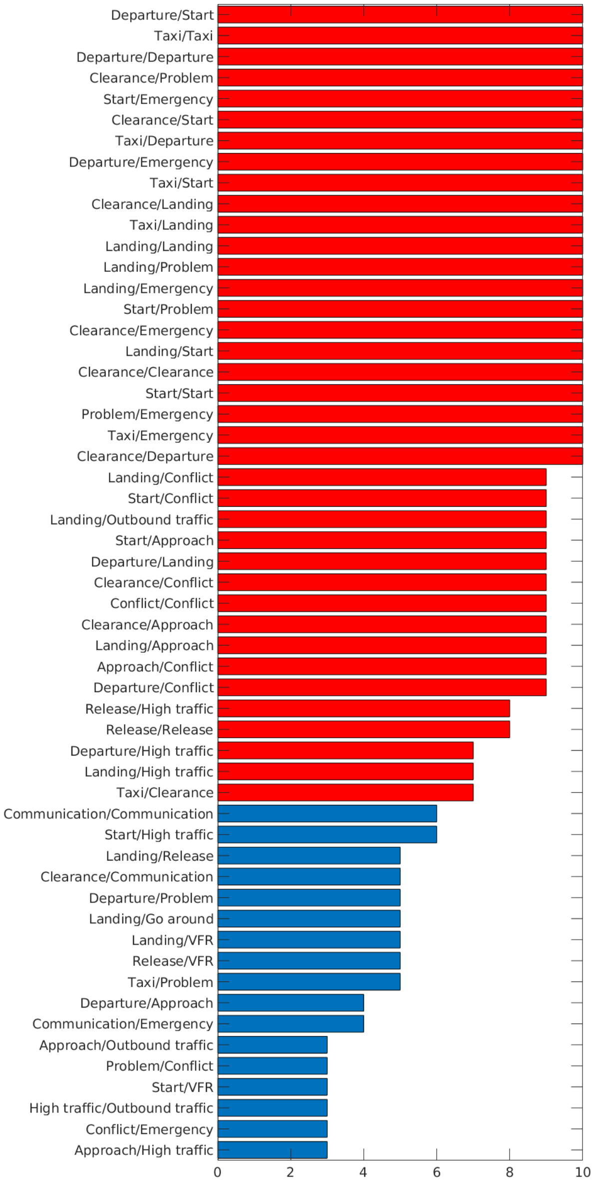


Fig. 3. Event pairs for the UJ setup ordered by max controller rating.

The detailed analysis can be found in Figure 5: We only

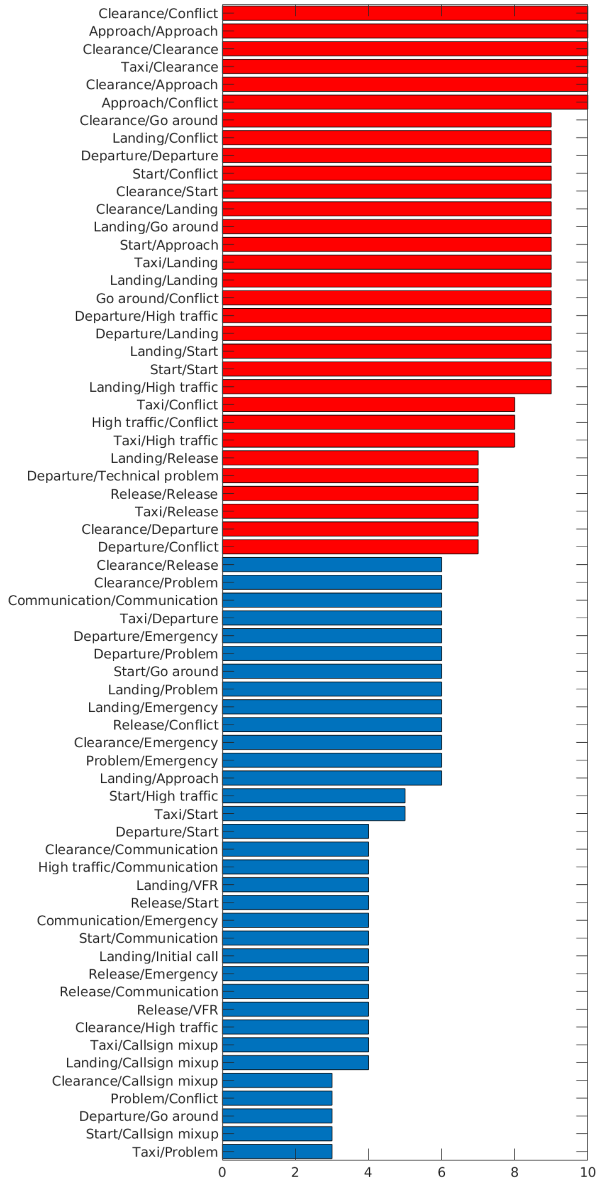


Fig. 4. Event pairs for the UN setup ordered by max controller rating.

show the dominated sub-pairs (because of space restrictions) and not all sub-pairs of a triple, and highlight the critical triples in orange. Most of the triples dominate at most one pair, however, there exist triples that dominate all of their sub-pairs. In the former case, only adding a third to one sub-pair increases the complexity rating, e.g., for the triple clearance/approach/conflict at a single airport, only adding an approach to the event pair clearance/conflict at a single airport will increase the complexity, while the event pairs approach/conflict and approach/clearance at a single airport already contain so much intrinsic complexity that adding the event clearance or conflict, respectively, cannot increase the controller rating. On the other hand, the triple clearance/landing/start dominates all of its sub-pairs w.r.t. the mean rating, that is, w.r.t. the average controller.

Moreover, we can observe that no critical triple contains the events emergency, call sign mix-up, communication, and problem. All critical event triples that dominate w.r.t the mean rating, dominate one sub-pair clearly, that is, here we suggest that the added event significantly increases the complexity.

C. *Consequences of Events and causing factors*

Finally, we filtered out consequences of (simultaneous) events at two airports, and analyzed which events contributed to these problematic consequences. Data from both conditions UN and UJ was used. The coding variables monitoring problem, small delay, mix-up of airports, switching airports, and communication problem were rated as consequences. The data set contained 96 situations with problematic consequences.

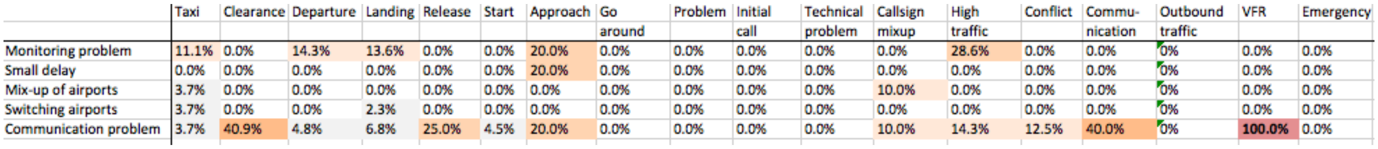
The rationale behind this analysis is that problematic consequences like a monitoring problem can be an indicator of a potentially risky, non-manageable situation, and that events that often lead to such consequences can also be considered as critical complexity factors. The results are shown in Figure 6. Some events often lead to problematic consequences, e.g., 40% of communication led to a communication problem, and—most significantly—100% of VFR traffic led to a communication problem. VFR was not one of the predefined scenario events. That is, we only know that VFR traffic was present if the ATCO mentioned it. Thus, 100% of mentions of VFR traffic coincided with a communication problem. On the other hand, go-arounds, technical problems, general problems, initial calls, outbound traffic and emergencies never were causing effect of a situation with a problematic consequence.

D. *Summary*

Our analysis led to three sets of critical complexity factors: first, pairs that lead to critical handling qualities for at least one controller or an average controller—as impossible or manageable only with limited situational awareness (SectionII-A). One main factor is the availability of relevant information. Within the switching conditions, emergencies at one airport reduced handling qualities which was not the case in the condition where both airports were visible to the controller. Furthermore, the ratio of situations with critical handling qualities was increased. Focussing on the list of complexity factors in both conditions, complexity is increased when ATCOs have to solve a traffic conflict at one airport and manage routine traffic at the second airport (from the 17 critical pairs for the mean rating and UN setup 9 pairs have a conflict at a single airport). Thus, the complexity is influenced when ATCOs need to prioritize tasks at two airports without proper rules to do so. A conflict is a high priority tasks. If traffic is at one airport, ATCOs have proper rules how to prioritize their tasks. These rules are needed also for multiple operations The rules could be learned from experience, or designed and trained, or scheduling should avoid these situations. The second list contains triples of events that dominate at least one of their sub-pairs and, hence, adding one of the events clearly increases the complexity of the situation for the ATCO (Section III.B). In particular, we can observe that adding a third event to two landings (either a departure, a release, a clearance, high traffic volume, a conflict at a single airport,

Situation	mean	min	max
Clearance/Start/Callsign	**3**	**3**	**3**
Start/Callsign mixup	*2,5*	*2*	*3*
Taxi/Start/Start	**3,5**	**2**	**5**
Start/Start	*3,454545455*	*1*	*9*
Taxi/Departure/Landing	**3,5**	**1**	**6**
Taxi/Departure	*3,2*	*1*	*6*
Landing/Start/Start	**3,625**	**1**	**9**
Start/Start	*3,454545455*	*1*	*9*
Taxi/Landing/Callsign	**4**	**4**	**4**
Landing/Callsign mixup	*3*	*2*	*4*
Taxi/Landing	*3,588235294*	*1*	*9*
Start/Start/Communicati	**4**	**4**	**4**
Start/Start	*3,454545455*	*1*	*9*
Release/Start/Start	**4**	**4**	**4**
Start/Start	*3,454545455*	*1*	*9*
Landing/Release/Release	**4,25**	**3**	**7**
Release/Release	*4,166666667*	*2*	*7*
Departure/Landing/Land	**4,25**	**1**	**9**
Landing/Landing	*4,090909091*	*1*	*9*
Departure/Departure/La	**4,25**	**1**	**9**
Departure/Departure	*3,619047619*	*1*	*9*
Landing/Landing/Release	**4,25**	**3**	**7**
Landing/Landing	*4,090909091*	*1*	*9*
Landing/Landing/Emerge	**4,5**	**3**	**6**
Landing/Landing	*4,090909091*	*1*	*9*
Departure/Departure/Em	**4,5**	**3**	**6**
Departure/Departure	*3,619047619*	*1*	*9*
Departure/Departure/Pro	**4,5**	**3**	**6**
Departure/Departure	*3,619047619*	*1*	*9*
Departure/Landing/Emer	**4,5**	**3**	**6**
Departure/Landing	*4,25*	*1*	*9*
Clearance/Departure/Pro	**4,5**	**3**	**6**
Clearance/Problem	*4*	*3*	*6*
Landing/Landing/Proble	**4,5**	**3**	**6**
Landing/Landing	*4,090909091*	*1*	*9*
Departure/Landing/Probl	**4,5**	**3**	**6**
Departure/Landing	*4,25*	*1*	*9*
Clearance/Problem/Emer	**4,5**	**3**	**6**
Clearance/Problem	*4*	*3*	*6*
Clearance/Emergency	*4,333333333*	*3*	*6*
Clearance/Landing/Probl	**4,5**	**3**	**6**
Clearance/Problem	*4*	*3*	*6*
Clearance/Landing/Emer	**4,5**	**3**	**6**
Clearance/Emergency	*4,333333333*	*3*	*6*
Clearance/Departure/Em	**4,5**	**3**	**6**
Clearance/Emergency	*4,333333333*	*3*	*6*
Clearance/Release/Releas	**5**	**4**	**6**
Release/Release	*4,166666667*	*2*	*7*
Start/Start/High traffic	**5**	**5**	**5**
Start/Start	*3,454545455*	*1*	*9*
Taxi/Start/High traffic	**5**	**5**	**5**
Taxi/Start	*3,5*	*2*	*5*
Landing/Start/High	**5**	**5**	**5**
Landing/Start	*3,625*	*1*	*9*
Clearance/Departure/Lan	**5,333333333**	**3**	**7**
Departure/Landing	*4,25*	*1*	*9*
Taxi/Release/Release	**5,333333333**	**3**	**7**
Release/Release	*4,166666667*	*2*	*7*
Clearance/Departure/Dep	**5,333333333**	**3**	**7**
Departure/Departure	*3,619047619*	*1*	*9*
Clearance/Clearance/Dep	**5,333333333**	**3**	**7**
Clearance/Clearance	*5,181818182*	*1*	*10*
Release/Release/Conflict	**6**	**6**	**6**
Release/Release	*4,166666667*	*2*	*7*
Landing/Landing/Approa	**6**	**6**	**6**
Landing/Landing	*4,090909091*	*1*	*9*
Start/Start/Go around	**6**	**6**	**6**
Start/Start	*3,454545455*	*1*	*9*
Taxi/Release/Conflict	**6**	**6**	**6**
Taxi/Release	*5,333333333*	*3*	*7*
Taxi/Departure/High	**6**	**6**	**6**
Taxi/Departure	*3,2*	*1*	*6*
Clearance/Release/Confli	**6**	**6**	**6**
Clearance/Release	*5*	*4*	*6*
Taxi/Clearance/Release	**6**	**6**	**6**
Clearance/Release	*5*	*4*	*6*
Taxi/Release	*5,333333333*	*3*	*7*
Taxi/Landing/High traffic	**6,333333333**	**5**	**8**
Taxi/Landing	*3,588235294*	*1*	*9*
Clearance/Clearance/Landing	**6,666666667**	**3**	**9**
Clearance/Clearance	*5,181818182*	*1*	*10*
Clearance/Landing/Landing	**6,666666667**	**3**	**9**
Landing/Landing	*4,090909091*	*1*	*9*
Taxi/Clearance/Clearance	**6,666666667**	**4**	**10**
Clearance/Clearance	*5,181818182*	*1*	*10*
Departure/Departure/Conflict	**7**	**7**	**7**
Departure/Departure	*3,619047619*	*1*	*9*
Landing/Landing/High traffic	**7**	**5**	**9**
Landing/Landing	*4,090909091*	*1*	*9*
Clearance/Clearance/Start	**7**	**3**	**9**
Clearance/Clearance	*5,181818182*	*1*	*10*
Departure/Departure/Technical	**7**	**7**	**7**
Departure/Departure	*3,619047619*	*1*	*9*
Departure/Landing/Conflict	**7**	**7**	**7**
Departure/Landing	*4,25*	*1*	*9*
Clearance/Start/Start	**7**	**3**	**9**
Start/Start	*3,454545455*	*1*	*9*
Clearance/Departure/Conflict	**7**	**7**	**7**
Clearance/Departure	*5,333333333*	*3*	*7*
Departure/Departure/High traffic	**7,5**	**6**	**9**
Departure/Departure	*3,619047619*	*1*	*9*
Departure/Landing/High traffic	**7,5**	**6**	**9**
Departure/Landing	*4,25*	*1*	*9*
Landing/High traffic	*7*	*5*	*9*
Clearance/Clearance/Conflict	**7,571428571**	**3**	**10**
Clearance/Clearance	*5,181818182*	*1*	*10*
Taxi/High traffic/Conflict	**8**	**8**	**8**
Taxi/High traffic	*6,75*	*5*	*8*
Taxi/Conflict	*7*	*6*	*8*
Landing/Landing/Conflict	**8,333333333**	**7**	**9**
Landing/Landing	*4,090909091*	*1*	*9*
Clearance/Landing/Conflict	**8,333333333**	**7**	**9**
Clearance/Landing	*6,666666667*	*3*	*9*
Clearance/Conflict	*7,571428571*	*3*	*10*
Clearance/Start/Approach	**9**	**9**	**9**
Clearance/Start	*7*	*3*	*9*
Start/Start/Approach	**9**	**9**	**9**
Start/Start	*3,454545455*	*1*	*9*
Clearance/Go around/Conflict	**9**	**9**	**9**
Clearance/Conflict	*7,571428571*	*3*	*10*
Start/Start/Conflict	**9**	**9**	**9**
Start/Start	*3,454545455*	*1*	*9*
Clearance/Clearance/Go around	**9**	**9**	**9**
Clearance/Clearance	*5,181818182*	*1*	*10*
Landing/Go around/Conflict	**9**	**9**	**9**
Landing/Conflict	*8,333333333*	*7*	*9*
Clearance/Start/Conflict	**9**	**9**	**9**
Clearance/Start	*7*	*3*	*9*
Clearance/Conflict	*7,571428571*	*3*	*10*
Clearance/Landing/Start	**9**	**9**	**9**
Landing/Start	*3,625*	*1*	*9*
Clearance/Landing	*6,666666667*	*3*	*9*
Clearance/Start	*7*	*3*	*9*
Clearance/Landing/Go around	**9**	**9**	**9**
Clearance/Landing	*6,666666667*	*3*	*9*
Landing/Landing/Go around	**9**	**9**	**9**
Landing/Landing	*4,090909091*	*1*	*9*
Start/Approach/Approach	**9**	**9**	**9**
Approach/Approach	*8*	*6*	*10*
Landing/Start/Conflict	**9**	**9**	**9**
Landing/Start	*3,625*	*1*	*9*
Landing/Conflict	*8,333333333*	*7*	*9*
Clearance/Approach/Approach	**9,5**	**9**	**10**
Approach/Approach	*8*	*6*	*10*
Approach/Approach/Conflict	**9,5**	**9**	**10**
Approach/Approach	*8*	*6*	*10*
Clearance/Clearance/Approach	**9,5**	**9**	**10**
Clearance/Clearance	*5,181818182*	*1*	*10*
Clearance/Approach/Conflict	**9,5**	**9**	**10**
Clearance/Conflict	*7,571428571*	*3*	*10*

Fig. 5. Triples of events (bold) with dominated sub-pairs (italic), critical triples are highlighted in orange.



	Taxi	Clearance	Departure	Landing	Release	Start	Approach	Go around	Problem	Initial call	Technical problem	Callsign mixup	High traffic	Conflict	Commu-nication	Outbound traffic	VFR	Emergency
Monitoring problem	11.1%	0.0%	14.3%	13.6%	0.0%	0.0%	20.0%	0.0%	0.0%	0.0%	0.0%	0.0%	28.6%	0.0%	0.0%	0%	0.0%	0.0%
Small delay	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	20.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0%	0.0%	0.0%
Mix-up of airports	3.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.0%	0.0%	0.0%	0.0%	0%	0.0%	0.0%
Switching airports	3.7%	0.0%	0.0%	2.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0%	0.0%	0.0%
Communication problem	3.7%	40.9%	4.8%	6.8%	25.0%	4.5%	20.0%	0.0%	0.0%	0.0%	0.0%	10.0%	14.3%	12.5%	40.0%	0%	100.0%	0.0%

Fig. 6. Consequences and percentage of an event that lead to that consequence. The color scale indicates how many percent of an event caused a problematic consequence..

or a go around) significantly increases the complexity of the situation for the ATCO. In all these situations the ACTO already has to manage aircraft movements simultaneously, possibly at the two different airports, any additional event induces critical handling qualities for the ATCO. We observe a similar behavior for the pairs of two departures and departure and landing. The third list contains factors that are likely to cause problematic consequences. Here, VFR traffic, higher traffic numbers and approaching traffic should be mentioned. Complexity is influenced by unforeseen events or traffic with unforeseen behavior. In Germany, VFR traffic does not require a flight plan, hence, VFR traffic constitutes unforeseen events for the ATCO's preplanned actions.

IV. CONCLUSION AND OUTLOOK

We identified a first set of possible complexity factors for multiple remote control: by analyzing the ATCO rating of situations in a simulation of an RTC environment, we identified events that on their own, or in co-occurrence with one or two other events drove both the ATCO mental workload and impaired situational awareness. We focused on factors leading to critical ratings. Of course, the data also contains various situations that were rated as non-critical, that is, that received a rating below 7. An interesting future work direction is the analysis of these non-critical situations to gain insight into well-manageable events and traffic situations.

Our analysis of the event pairs and triples demonstrates that there is not a single factor, but the interplay of events at both airports, that drives the complexity. This result pattern is known from safety research. The concept of the human performance envelope also addresses this problem [3]. Basically, not a single factor can explain performance breakdowns or critical events but the interplay of several, sometimes marginal, events. This paper is a starting point for further research in the factors driving mental workload for RTC operations. Hence, the events identified in this paper should be part of a study that aims to give a quantitative measure for the workload of an RTC controller.

ACKNOWLEDGMENT

This research is a part of the CAPMOD project supported by the Swedish Transport Administration (Trafikverket) and in-kind participation of LFV.

REFERENCES

[1] G. Chatterji and B. Sridhar. Measures for air traffic controller workload prediction. In *1st AIAA, Aircraft, Technology Integration, and Operations Forum*, page 5242, 2001.

[2] D. Delahaye and S. Puechmorel. Air traffic complexity: towards intrinsic metrics. In *Proceedings of the third ATM Seminar*, 2000.

[3] T. Edwards. *Human performance in air traffic control*. PhD thesis, University of Nottingham, 2013.

[4] EUROCONTROL ACE Group. Complexity metrics for ansp benchmarking analysis. EUROCONTROL, April 2006.

[5] G. Flynn, A. Benkouar, and R. Christien. Adaptation of workload model by optimisation algorithms. Technical report, EUROCONTROL, 2005.

[6] D. Gianazza. Learning air traffic controller workload from past sector operations. In *ATM Seminar*, 2017.

[7] B. Hilburn. Cognitive complexity in air traffic control: A literature review. *EEC note*, 4(04), 2004.

[8] B. Josefsson, T. Polishchuk, V. Polishchuk, and C. Schmidt. Scheduling Air Traffic Controllers at the Remote Tower Center. In *DASC*, September, 2017.

[9] P. Kopardekar. Dynamic density: A review of proposed variables. *FAA WJHTC internal document. Overall conclusions and recommendations, Federal Aviation Administration*, 2000.

[10] P. Kopardekar, T. Prevot, and M. Jastrzebski. Traffic complexity measurement under higher levels of automation and higher traffic densities. *Air Traffic Control Quarterly*, 17(2):125–148, 2009.

[11] A. Koros, P. S. Della Rocco, G. Panjwani, V. Ingurgio, and J.-F. D'Arcy. Complexity in Airport Traffic Control Towers: A Field Study. Part 2: Controller Strategies and Information Requirements. Technical report, Federal Aviation Administration Technical Center, 2006.

[12] A. Koros, P. S. Rocco, G. Panjwani, V. Ingurgio, and J.-F. D'Arcy. Complexity in Air Traffic Control Towers: A Field Study. Part 1. Complexity Factors. Technical report, Federal Aviation Administration Technical Center, 2003.

[13] S. Loft, P. Sanderson, A. Neal, and M. Mooij. Modeling and predicting mental workload in en route air traffic control: Critical review and broader implications. *Human Factors*, 49(3):376–399, 2007.

[14] R. H. Mogford, J. Guttman, S. Morrow, and P. Kopardekar. The Complexity Construct in Air Traffic Control: A Review and Synthesis of the Literature. Technical report, CTA INC MCKEE CITY NJ, 1995.

[15] C. Möhlenbrink, M. Friedrich, A. Papenfuss, M. Rudolph, M. Schmidt, F. Morlang, and N. Furstenau. High-fidelity human-in-the-loop simulations as one step towards remote control of regional airports: A preliminary study. In *ICRAT*, 2010.

[16] C. Möhlenbrink and A. Papenfuss. ATC-monitoring when one controller operates two airports research for remote tower centres. *Proceedings of the Human Factors and Ergonomic Society annual meeting*, 55(1):76–80, 2011.

[17] C. Möhlenbrink, A. Papenfuss, and J. Jakobi. The role of workload for work organization in a remote tower control center. *Air Traffic Control Quarterly*, 20(1):5, 2012.

[18] F. Netjasov, M. Janić, and V. Tošić. Developing a generic metric of terminal airspace traffic complexity. *Transportmetrica*, 7(5):369–394, 2011.

[19] M. Peters. HMI Laboratory Report 8: Analysis of Critical Situations at Remote Tower Operated Airports. DLR, Institut für Flugführung, Braunschweig, 2012.

[20] B. Sridhar, K. S. Sheth, and S. Grabbe. Airspace complexity and its application in air traffic management. In *2nd USA/Europe Air Traffic Management R&D Seminar*, pages 1–6, 1998.

[21] J. D. Welch, J. W. Andrews, B. D. Martin, and B. Sridhar. Macroscopic workload model for estimating en route sector capacity. In *Proc. of 7th ATM Seminar, Barcelona, Spain*, page 138, 2007.

[22] E. Zohrevandi, V. Polishchuk, J. Lundberg, Å. Svensson, J. Johansson, and B. Josefsson. Modeling and analysis of controller's taskload in different predictability conditions. In *Proc. of 6th SESAR Innovation Days*, 2016.