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DOI
10.2514/6.2021-0655

Publication date
2021

Document Version
Final published version

Published in
AIAA Scitech 2021 Forum

Citation (APA)
Lo, J., & Bouarfa, S. (2021). Agent-based analysis of airline and railway command and control systems. In *AIAA Scitech 2021 Forum* (pp. 1-29). (AIAA Scitech 2021 Forum). American Institute of Aeronautics and Astronautics Inc. (AIAA). https://doi.org/10.2514/6.2021-0655

AIAA SciTech Forum
11–15 & 19–21 January 2021, VIRTUAL EVENT
AIAA Scitech 2021 Forum

10.2514/6.2021-0655

Agent-Based Analysis of Airline and Railway Command and Control Systems

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Abstract

Airline and train operations are feasible thanks to the Command and Control systems which involve interactions between human operators, technology, and procedures. In view of the expected growing demand, significant changes in these C2 systems are in development in many countries. Such changes can lead to both positive and negative emergent behaviours. One of the promising approaches to capture this behaviour is agent-based modelling. In order to develop and implement a generic agent-based model for C2 systems, this paper compares and evaluates two C2 systems from the railway and airline domains. The paper conducts a systemic agent-based analysis that explores various dimensions including organizational structure; agents characteristics; operational uncertainties and workflows.

Keywords: socio-technical systems, airline C2 system, railway C2 system, agent-based analysis, situation awareness, disruption management

1. Introduction

Societies rely on networks of sectors to fulfill basic needs such as healthcare, energy and transportation. Each sector has its own historical and geopolitical developments, however they are all bound by their characteristic as being complex socio-technical systems: they strongly rely on engineering and technological equipment, but simultaneously also heavily rely on the involvement of human operators (De Bruijn & Herder, 2009). Technology plays a central role as does the social context in which actors operate.

As technological developments in automation and artificial intelligence are rapidly advancing, different sectors are using these developments to automate different processes to optimize performance. The recognition that technology increasingly overlaps with human tasks is a system design change that should be based on careful and thorough understanding of a socio-technical system. A systems perspective could aid in obtaining an integral knowledge base (Sheridan, 2010). The complex adaptive systems (CAS) perspective specifically recognizes the existence of subsystems, each with an interdependence of human, technical and physical components that are reorganizing, changing and evolving (Holland, 1992; McCarthy, 2003). CAS also connects the system perspective with artificial intelligence through agent-based modeling and simulation (Berry, Kiel, & Elliott, 2002; Macal & North, 2009). A cognitive (agent-based) model of a human operator can be used to for example, predict individual performance, support human operators in

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their decision-making and collaborate with operators or other agents (Rehling, Lovett, Lebiere, Reder, & Demiral, 2004; Wooldridge & Jennings, 2009).

Both airline and railway operations are subject to various internal and external disruptions of different nature that implicitly test their resilience on a regular basis. The main disruptors are mechanical problems, severe weather, congestions at airports and train stations, and industrial actions (strikes). Such events may interact with each other and potentially trigger other events that may span over different temporospatial scales, ranging from affecting one aircraft or train up to a group of aircraft or trains. In order to deal with such disruptions both railway and airlines companies have established Command and Control (C2) centers to monitor operations in real time and manage disruptions. For both C2 systems, such disruptions tend to cause domino effects in their highly optimized timetables. The goal of both systems is to deliver customer promise despite these disruptions. In doing so, they aim at minimizing costs incurred during recovery, and return to the original schedule as soon as possible. Therefore mitigation of disruptions and fast recovery of C2 systems are strongly desired. Agent-based modelling could be used to support operators, for example through offering decision support systems (Aydoğan, Lo, Meijer, & Jonker, 2014; Van den Berg, 2018; Bouarfa et al 2016, 2018).

Previous work comparing both the railway and airline domains provided novel insights on passenger behaviour (Stedmon, Lawson, Lewis, Richards, & Grant, 2016). Hanne & Dornberger (2010) focused on comparing planning processes by both airlines and railway, and concluded that although the two domains have significant similarities, i.e. transport of people and goods according to specified schedules, the dissimilarities seem to prevail due to the mostly separate developments of these fields. Givoni & Banister (2006) examined integrating railway and airline operations demonstrating social and economic benefits. Other comparative studies focus on the environmental impact of airline and railway operations including pollution (Givoni 2007) and noise (Elmenhorst et al 2012). However, to the best of the author's knowledge, there has been no prior comparison of the C2 systems from both the airline and railway domains in the literature.

This paper aims at comparing both C2 systems by firstly identifying and describing the fundamental similarities and differences of these domains in terms of system's characteristics. An agent-based analysis is performed with regards to different components. The findings can be used to develop a generic agent-based model of a C2 system, conduct sensitivity analysis, and further optimize the design of existing C2 systems.

Drawing from multiple frameworks on delineating socio-technical systems, three spaces are explored: the institutional space (i.e. governance, procedures and rules); the product space (i.e. the hardware used in the system such as rolling stock, runway, track, schedules, traffic management system); and the social space (i.e. operators and their roles and tasks) (Geels, 2004; Reich & Subrahmanian, 2015). The analysis in this paper uses the following components to compare the railway and aviation C2 system:

- **Institutional space:** purpose of the C2 system (section 3); system phases (section 4), organizational structure (section 5), recovery strategie (section 8) and operational workflows (section 9)
- **Product space:** operational uncertainties (section 7)
- **Social space:** situation awareness (section 6)

2. CAS perspective

The Complex Adaptive Systems perspective distinguishes three levels in a C2 system: the agent, network and system level (Bekebrede & Meijer, 2009). The agent level is focused on agents (i.e. operators) and their behavior and adaptations as individuals or teams. Key properties of agents include agent diversity and adaptiveness. The network level is focused on the network dynamics with regards to the interaction between agents, interaction with formalized systems and network evolution regarding human, technical and physical components. The system level is focused on properties such as the organization or teams of agents, path dependency of processes, and robustness and instability in terms of processes and strategies.

Emergent behavior by a C2 system results from interactions between the various human operators, technical systems, and procedures. The emergence concept is central to complex socio-technical systems and refers to how collective properties arise from the properties of the parts. Examples in the Airline C2 system include the effect of new airline C2 protocols on airline performance (Bouarfa et al 2016), or consequences ascribed to a change in operator’s decision making and the way they interact with their environment. To understand the behavior of a complex socio-technical system such as an airline or railway C2 system we must understand how the parts act together to form the behavior of the whole (Bar-Yam 2003). One of the promising approaches to achieve this is the agent-based modelling paradigm. Burmeister et al (1997) discuss the benefits of using an agent-based approach in domains that are functionally or geographically distributed into autonomous subsystems, where the subsystems exist in a dynamic environment, and the subsystems have to interact more flexibly. According to Burmeister, agent-based modeling can be used to structure and appropriately combine the information into a comprehensible form. For a large complex system such as a traffic system, they provide the tools for analyzing, modeling, and designing the whole system in terms of its subsystems, each with its own set of local tasks and capability. The Integration can then be achieved by modeling the interactions among the subsystems. So agent-based modeling provides abstraction levels that make it simpler and more natural to deal with the scale and complexity of problems in these systems. Agent components can be described at a high level of abstraction, yet the resulting systems are very efficient. Burmeister et al (1997) conclude that agent-based modeling reduces the complexity in systems design by making available abstraction levels that lend themselves to a more natural way of modeling the problem domain. They enhance the robustness and adaptivity of systems by virtue of increasing the autonomy of subsystems and their self-organization.

In the context of C2 systems, in particular where different actors, hardware, and software are interacting elements of a complex socio-technical system, we consider agents as autonomous entities that are able to perceive their environment and act upon this environment (see Figure 1). These agents may be humans, systems, organizations, and any other entity that pursues a certain goal. The agent environment is understood as the surrounding agent that includes both human and non-human agents.

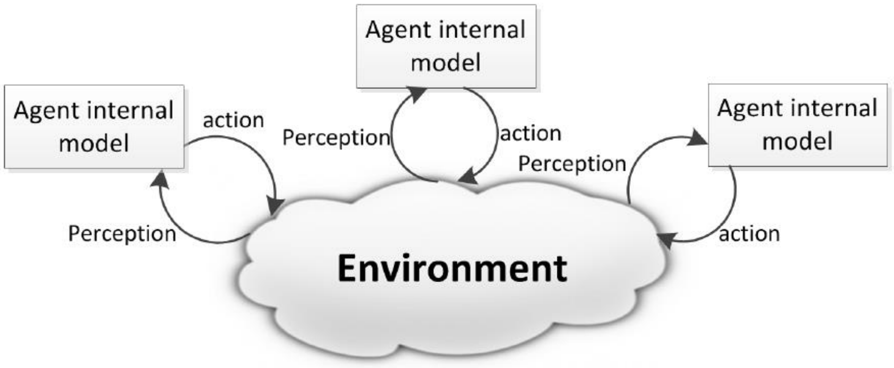


Figure 1: Agents in a C2 system

3. C2 System Purpose

The purpose of the railway and aviation C2 systems is described in this section in terms of their Key Performance Objectives.

3.1 Railway C2 System

The main purpose of railway traffic control is to manage train traffic according to schedule in a safe manner. However when disruptions occur there is a higher chance that safety, reliability and punctuality are at risk. In a disruption state, railway traffic control aims to ensure that safety is achieved by minimal damage of trains through collisions with other trains and objects or derailment, but also minimal red signal passages of trains. Maintaining the schedule or timetable is obtained by minimizing deviations of this schedule through delays or cancellations of trains (Lo, 2020). Not all values are transformed into performance indicators, such as for example safety (Steenhuisen, 2009). Current key performance indicators that have been determined together with the Dutch ministry of infrastructure and water management are for example passenger punctuality at the main domestic lines, train punctuality at regional lines, impactful disruptions of the infrastructure, and customer satisfaction (Beheerplan 2020-2021, 2020). However, in terms of competing values and operational perception, a previous study in Dutch railway traffic control indicated a gap between the organizational performance indicators and those preferred by train traffic controllers (Lo, Pluyter, & Meijer, 2015). Additionally a relative strong diversity in the preference of performance indicators by operators was found.

3.2 Airline C2 System

The main purpose of airline disruption management is to ensure that operations adhere as closely as possible to the airline published schedule and the shorter-term planning of fleet assignment, aircraft routing and crew assignment (Figure 3). According to Bruce (2011), an Airline C2 system aims at planning and coordinating disruption management to achieve network punctuality and customer service while utilizing assets effectively and minimising cost, in which multiple performance indicators are competing (Blom & Bouarfa 2016). Peters (2006) defines the purpose of AOC as to diminish the difference between projected and realised quality as much as possible. Kohl et al. (2007) identifies three objectives in disruption management: (1) get back to the plan as soon as possible, (2) minimize real costs and (3) deliver customer promise. The airline must also comply with the international standard set by ICAO such as the ones in relation safety.

4. C2 System Phases

This section compares systems phases in both the railway and airline C2 system. The phases involve short-term, mid-term, and long-term planning phases.

4.1 Railway C2 System

The system phases in the railway sector can be described in strategic (long-term), tactical (medium-term) and operational (short-term to real-time) (Lo, 2020; Marinov, Şahin, Ricci, & Vasic-Franklin, 2013; Van den Top, 2010). Figure 2 depicts the design process in railway operations from real-time to an undefined number of years.

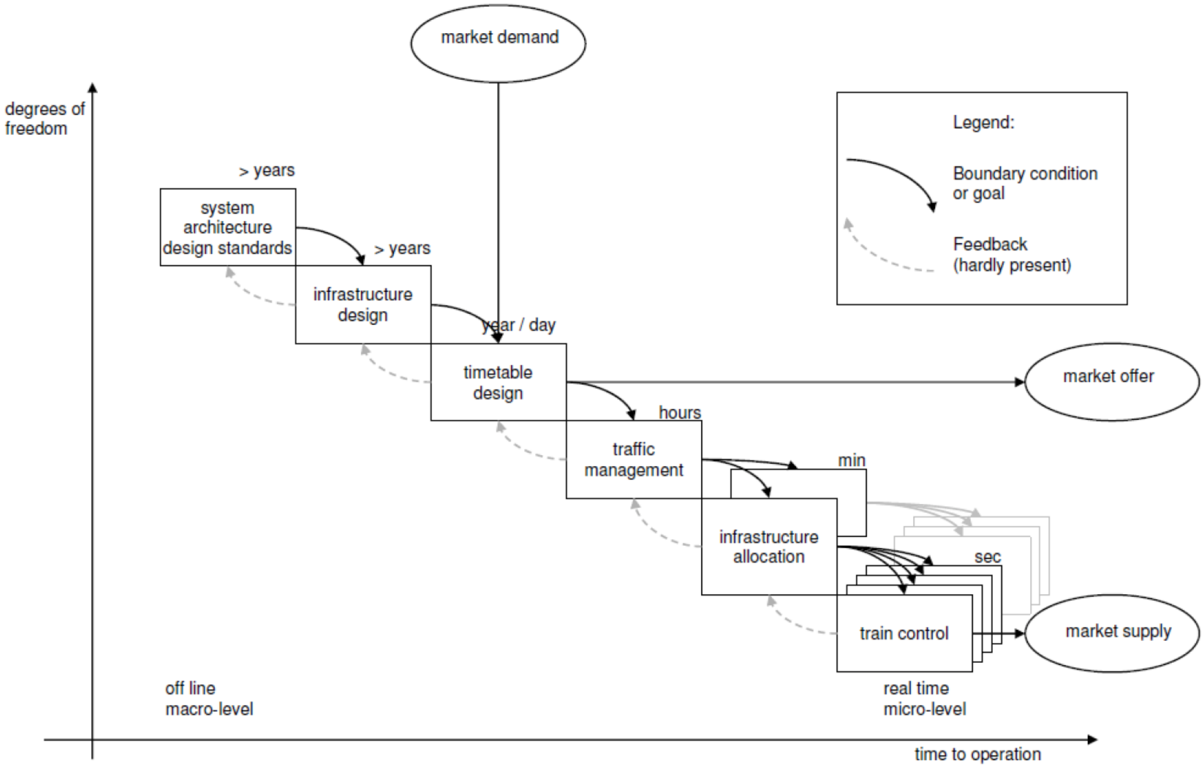
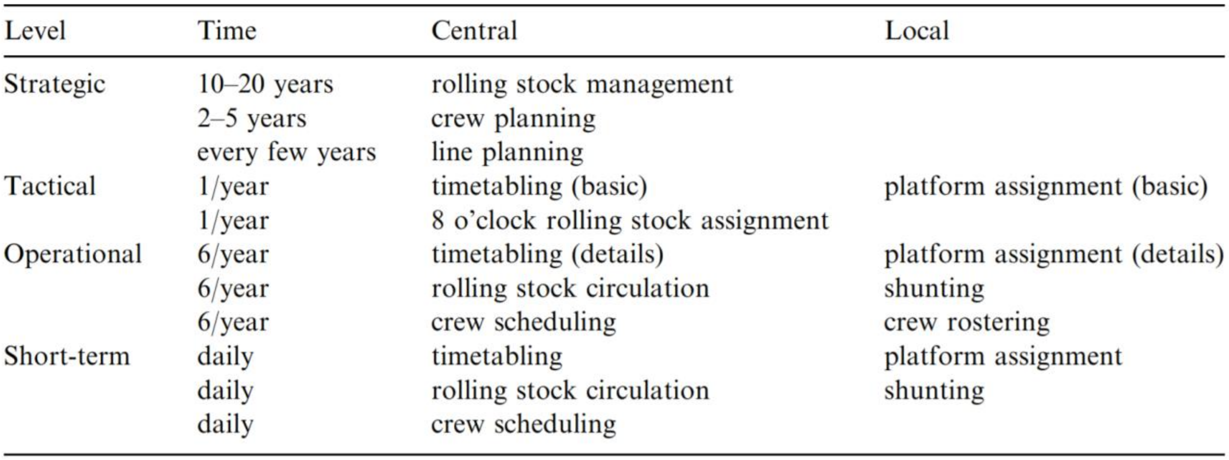


Figure 2: Design process in railway operations (Van den Top, 2010)

The **strategic** phase is aimed at long term system design of the railway sector. For instance, the Dutch government decided in 2010 on the capacity increase of the infrastructure that would result in more trains on the railway network and a higher frequency of trains in the timetable by 2028 (Ministerie van Infrastructuur en Milieu, 2011; 2019). However, along with an increase in trains, more operational complexity is expected, in which the use of decision-support systems is needed (D'Ariano, 2009). On a European level, a first Memorandum of Understanding has been signed in 2005 by the European Commission, the European rail manufacturers, infrastructure managers and railway undertakings to implement a new standardized safety system - European Rail Traffic Management System (ERTMS) (Memorandum of Understanding, 2016). Estimations are that the transformations of the safety system in European countries will vary from implementation in 2021 in Denmark until roughly 2037 by many other European countries (European commission, 2018; 2020). Through ERTMS a next step is taken in the railway sector towards digitalization in signalling, infrastructure, traffic management and trains. Due to the standardization of technical systems an increase in international passenger and freight traffic will also be made possible more easily.

The **tactical** phase involves the planning of infrastructure design and maintenance and the development of new timetables. The design process of infrastructural changes are planned years ahead (Van den Top, 2010). The process of line planning development on a macro level is started years ahead and reaches its final stage one year ahead before implementation, in which the timetable is specified on a micro level (Huisman, Kroon, Lentink, & Vromans, 2005; Marinov, Şahin, Ricci, & Vasic-Franklin, 2013, Van den Top, 2010). Table 1 depicts an overview of the planning problems that are identified by the Dutch principle passenger railway operator Nederlandse Spoorwegen (NS). Herein a differentiation is made between operational and short-term planning, in which operational refers to the basic scheduling problems that occur every two months, while short-term refers to detailed modifications for the individual days. Problems can also occur in different physical locations: they can have a central or local impact.

Table 1: Identified planning problems for domestic lines at NS (Huisman, Kroon, Lentink, & Vromans, 2005)



Level	Time	Central	Local
Strategic	10–20 years	rolling stock management	
	2–5 years	crew planning	
	every few years	line planning	
Tactical	1/year	timetabling (basic)	platform assignment (basic)
	1/year	8 o'clock rolling stock assignment	
Operational	6/year	timetabling (details)	platform assignment (details)
	6/year	rolling stock circulation	shunting
	6/year	crew scheduling	crew rostering
Short-term	daily	timetabling	platform assignment
	daily	rolling stock circulation	shunting
	daily	crew scheduling	

In the **operational** phase, operators are managing the train traffic flow from roughly a day before until real-time. For railway traffic control this is mostly focused on monitoring the train traffic flow, maximizing infrastructure capacity, minimizing train delays, and processing ad hoc requests for infrastructural capacity by freight or passenger train operating companies (i.e. new train paths), and disruption management. Freight and passenger train operating companies also need to consider the circulation of rolling stock, maintenance routing of rolling stock and crew scheduling next to timetable rescheduling (Huisman, Kroon, Lentink, & Vromans, 2005).

4.2 Airline C2 System

The **strategic** phase consists of different stages with the first stage being the development of the timetable. In this stage, profitable routes and frequencies to fly under demand uncertainty are determined. These routes will be used to schedule departure time, arrival time and flight destination.The next stage of the strategic phase is resource allocation and consists of several steps. It is common practice that this starts with the aircraft resource by assigning fleet followed by individual aircraft i.e. tail assignment (Kohl et al., 2007). For the assignment the planners take into account factors like revenue per seat, noise restrictions, maintenance requirements and even gate restrictions. The result of the aircraft allocation is defined as the aircraft rotation schedule. By using this schedule, the crew resource is allocated. This stage comprises two actions: crew pairing and crew rostering. Crew pairing is the process of selecting crew that have to stick together during outbound and inbound flights while crew rostering involves linking designated crew with named individuals (Clausen et al., 2009). In addition to the time table and resource allocation, a tactical element is already introduced in the strategic phase to aid AOC, also referred to as pro-active decision-making. A certain degree of robustness is incorporated into the schedule to ensure continuous feasibility.

The transition from the strategic to the **tactical** phase is also a transition of responsibility. One day before the schedule is operative; the duty manager of AOC will review the schedule. There is a possibility that the duty manager rejects the schedule if it lacks robustness and/or flexibility. When the schedule is accepted by the duty manager (also referred to as the ‘handshake’) the AOC will be responsible for the tactical phase of the airline operational planning. Kohl et al. [25] present the airline disruption management process that is in use by many airlines. The process has six steps namely: 1) Operation monitoring; 2) Assessment; 3) Identifying possible solutions; 4) Evaluating possible solutions; 5) Taking decision; and 6) implementing decision. According to Castro and Oliveira (2011), for steps 2-5, AOC centers rely heavily on the experience of their controllers who use some rules-of-thumb (a kind of hidden or tacit knowledge) that exist in the AOC centers.

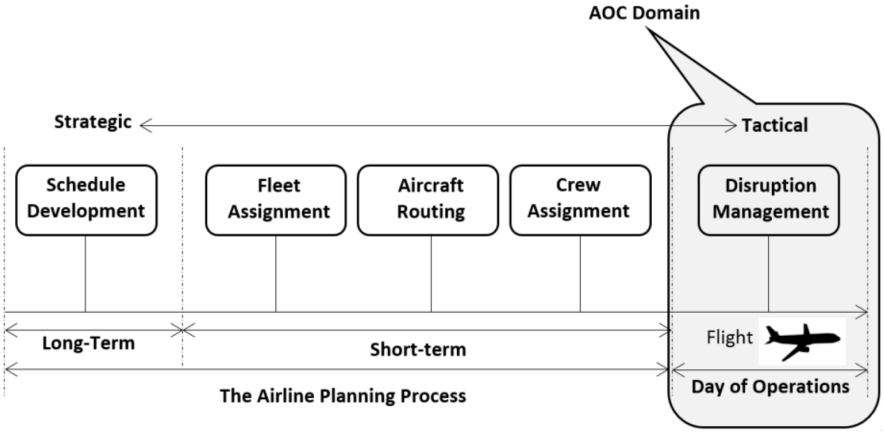


Figure 3: Airline planning and airline disruption management

5. Organizational Structure

This section provides an overview of the main stakeholders and agents involved in the railway and airline C2 systems together with a description of their main role.

5.1 Railway C2 System

When zooming in on the operational phase in the railway C2 system a distinction can be made in terms of the organization (railway, freight or passenger traffic control), the co-location of operators and the function of operators. Figure 4 depicts the organizational structure of operators and their co-location.

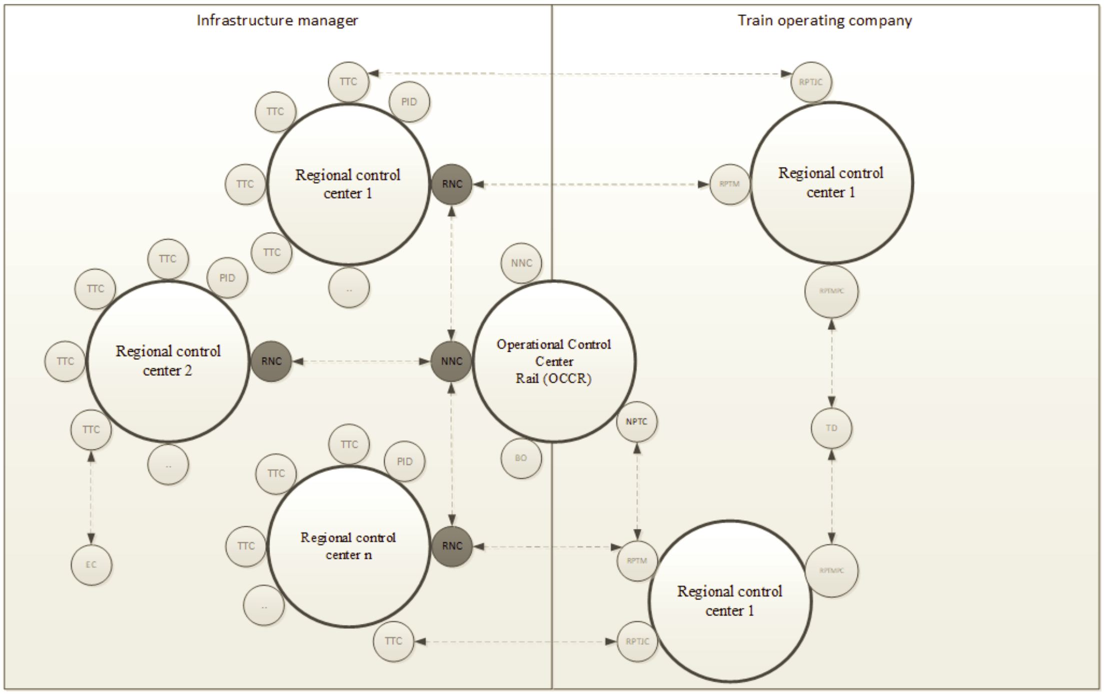


Figure 4: Organization of railway and passenger traffic control centers in the Netherlands

Table 2 provides an overview of the function of operators in railway and passenger traffic control. It should be noted that the role at passenger traffic control operators can vary between freight passenger traffic organizations. The current roles are mainly based on the principle Dutch passenger traffic organization NS.

Table 2: Functions of operators in railway and passenger traffic control

Organization	Agent	Role Description
Railway traffic control	Train traffic controller (TTC)	Assigns and manages infrastructure according to schedule in a timely and safe manner
Railway traffic control	Regional network controller (RNC)	Manages the train traffic flow according to schedule in a timely, safe and transparent manner against a high customer value, within a control center
Railway traffic control	National network controller (NNC)	Manages the train traffic flow according to schedule in a timely, safe and transparent manner against a high customer value, on a national level
Railway traffic control	Officier van Dienst Spoor (OvD-S)	Acts as operational supervisor at the national control center (OCCR)
Railway traffic control	Emergency coordinator (EC)	Coordinates from the physical location of the emergency
Railway traffic control	Back-office (BO)	Supports in the communication and coordination during incidents
Railway traffic control	Officier van Dienst Verkeersleiding (OvD-V)	Acts as operational supervisor at a regional control center
Freight or passenger train operating company	Train drivers (TD)	Operates trains on the rail network carrying passengers or freight, or shunting rolling stock to/from yards
Passenger traffic control	Regional passenger traffic monitor (RPTM) (role dissolved but relevant for section 9.1)	Manages the rescheduled timetable, crew and rolling stock on a national level
Passenger traffic control	Regional passenger traffic operational coordinator	Acts as operational supervisor at the regional passenger traffic control center for crew and rolling stock rescheduling
Passenger traffic control	Regional passenger traffic junction coordinator (RPTJC)	Manages rolling stock at stations that deviate from the schedule
Passenger traffic control	Regional passenger traffic rolling stock coordinator (RPTJC	Coordinates the rescheduling of rolling stock during disruptions.
Passenger traffic control	Regional passenger traffic passenger coordinator	Coordinates the rescheduling of crew and rolling stock during disruptions.
Passenger traffic control	National passenger traffic controller (NPTC) (role dissolved but relevant for section 9.1)	Coordinates the disruption mitigation at the national control center (OCCR) with the NNC
Passenger traffic control	Passenger information dispatcher (PID)	Coordinates the information about maintenance work and disruptions to passengers and communication on stations

5.2 Airline C2 System

Each airline comprises interactions between a variety of facilities, human operators, technical systems, regulations and procedures, and is embedded in the larger air transportation system that comprises airports, other airlines, and ATC centers. Each day of operation, the system is subject to various disruptions ranging from bad weather, passenger delays, to aircraft and crew-related problems. The current practice of recovering from disruptions in AOC involves multiple teams of collaborating human operators.

Figure 5 gives an overview of a typical airline C2 system showing the human agents, the technical systems, and the interactions between the AOC agents and their external world (while the exact terminologies may vary per airline). It should be noted that in addition to the agents shown in Figure 5, there exist other services in AOC centers which provide support for AOC operators (e.g. operational engineering). In addition, a crisis center which coordinates activities after an accident or incident is often an integrated part of an airline's AOC center.

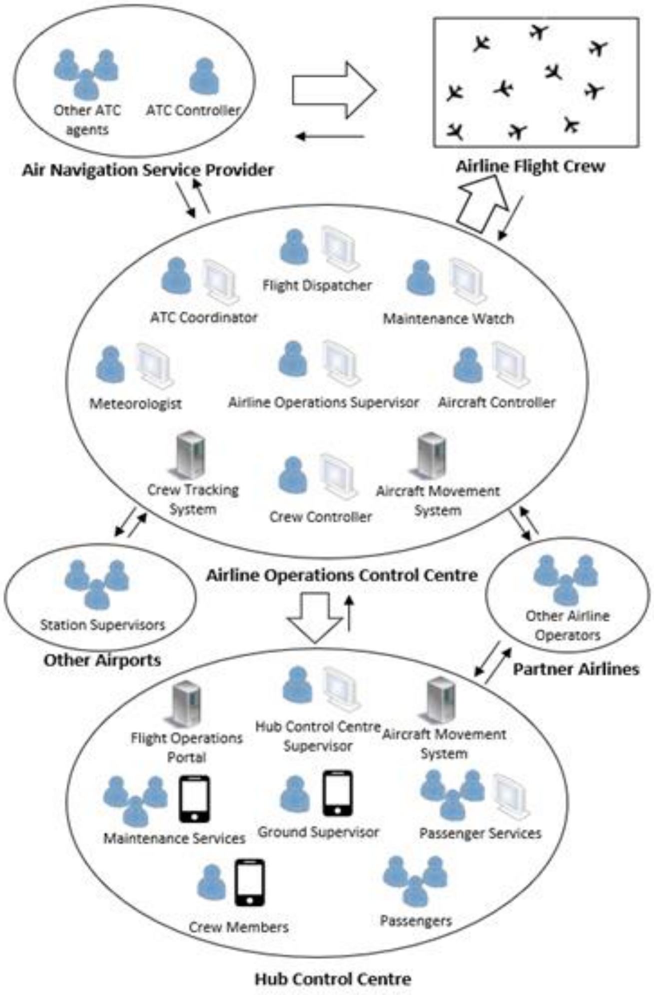


Figure 5: Organization of an airline operation control center

Table 3 provides an overview of the main agents involved in the airline C2 system together with a short description of their responsibility.

Table 3: Functions of operators in Airline Operations Control

Agent	Role Description
Airline Operations Supervisor (AOS)	Oversees the whole disruption management process and supervise various specialist airline controllers
Aircraft Controller (ACO)	Manages the aircraft resource.
Crew Controller (CCO)	Manage the resource crew. Monitors the check in and check out of crew and updates crew roster
Station Operations Controller (SOC)	Considers and minimize the impact of decisions on the passengers.
Flight Dispatcher (FD)	Flight planning, flight progress monitoring and weather monitoring
Meteorological Bureau (MB)	Weather Monitoring
Ramp Control (RC)	Load Control
Maintenance Department (MD)	Coordinating and planning of scheduled and unscheduled maintenance
Local Technician (LT)	Performing technical diagnosis
Flight Crew (FC)	Operating flights within their flight duty time limitations
Ground Operations (GO)	Performing turn-around processes of the flights
Airports (AIRP)	Assigning gates and parking bays for aircraft
Partner Airlines (PA)	Providing rebooking seats and spare parts to allied airlines

6. Situation Awareness

Emerged from aviation psychology, the cognitive construct of situation awareness (SA) intended to describe the pilot's comprehension at tactical flight operations (Durso & Gronlund, 1999). One of the best-known definitions of situation awareness from a psychological approach is by Endsley (1988): "The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future". Three levels of SA can be distinguished: level 1 SA - perception (of the elements in the environment, e.g. identification of an aircraft, mountains, warning light etc. by pilots), level 2 - comprehension (of the current environment or situation, e.g. determining the status of a power plant system through disparate bits of data by a power plant operator), level 3 - projection (of the future status, e.g. predicting which aircraft runways will be free in order to prevent collisions by traffic controllers) (Endsley, 1995).

The three-level model by Endsley (1988) has been widely accepted as a definition for situation awareness on the individual level. However, this is not the case for the theoretical acceptance of situation awareness beyond the individual level. Situation awareness beyond the individual level, i.e. on a team, network or system level has been approached from multiple theoretical perspectives (Lo, 2020), such as the classic psychological information-processing perspective like the three-level model (Endsley, 1988), the team cognition perspective (Cooke, Gorman, Myers, & Duran, 2013), and distributed situation awareness which builds on the distributed cognition perspective (Hutchins, 1995). Often team/network/system situation awareness is operationalized through the communication and coordination between operators (Cooke, Gorman, Myers, & Duran, 2013; Stanton, Stewart, Harris, Houghton, Baber, McMaster, et al., 2006). The analysis of situation awareness and communication between operators on a system level can be used to obtain insights into the performance and resilience of the system.

As the current paper focuses on the description of the aviation and railway system and its operators, the current section focuses on the situation awareness development of - and between - multiple operators. Description of communication and coordination between operators for railway and aviation will focus on shared displays, verbal communication and communication through information systems.

6.1 Railway C2 System

In the majority of cases, disruptions are notified to the train traffic controllers who receive a phone call by train drivers or can detect malfunctions in the infrastructure by certain symbols in their traffic control system. An important task for train traffic controllers is therefore to "constantly monitor the evolution of train traffic through a traffic control system in his/her responsibility territory and define the current state of the traffic; by forecasting, identifying (detect) and then resolving traffic problems, or conflicts, well before they actually occur" (Marinov, Şahin, Ricci, & Vasic-Franklin, 2013, p.62). It is therefore expected that train traffic controllers develop their situation awareness at shift changes and during their shift actively monitor their traffic control systems. The most important parts of their train traffic control system are their 1) planning screen (depicting for each train for example their train number, planned activity (arrival, departure, passage), route in terms of tracks, status of the route setting automation), 2) overview screen (depicting an geographical area with infrastructure, track numbers and location of trains) and 3) detail screen (depicting more detailed information of the infrastructure such as switches and signals, and interface for safety related actions, such as revoking signals and manually setting routes. Figure 6 illustrates a workstation of a train traffic controller.

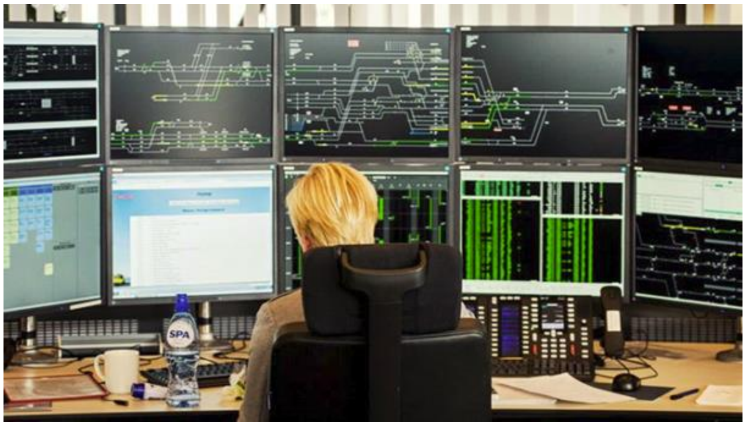


Figure 6: Workstation of a train traffic controller in the Netherlands.

In a previous study it was found that not co-location of operators but shared displays were the primary driver of the development of situation awareness in a team (Lo & Meijer, 2019). It is however considered that co-location can still contribute to the overall situation awareness development in comparison to separate locations (Lo & Meijer, 2020). In terms of the shared displays, train traffic controllers share identical screens (excluding the activated automation) when sharing responsibility for the same geographical area together with other train traffic controllers (see Figure 7).

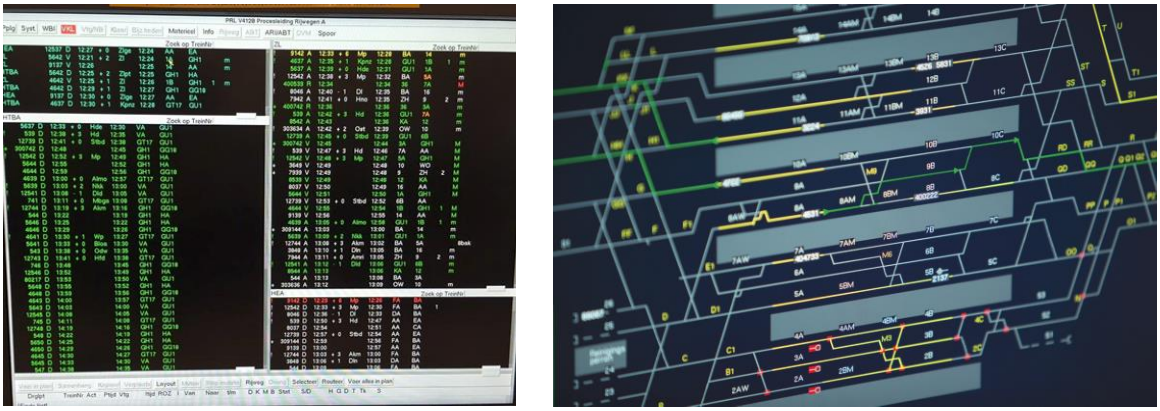


Figure 7: Planning screen (left) and one of three or four overview screens of train traffic controllers (right)

Train traffic controllers also share these screens with passenger traffic operators, specifically the RPTJC, who is responsible for the same geographical area. In order for observers to track when changes have been made by train traffic, markings are shown in the planning screen. The RNC also makes use of the TTC's overview screens. In turn, the RNC makes use of a time-graph diagram that is used by the NNC. In general operators who need to collaborate make use of one or more shared displays, also across different organizations. Additionally, network controllers across organizations also make use of a digital platform to log disruptions and their status updates.

Verbal communication is currently one of the most important means to develop situation awareness on a network level. Section 9.1 will discuss and provide an example of a conducted study. It is expected that digitalization trends would facilitate less verbal communication and more 'silent communication' by increasingly making use of (selective) shared displays or digital platforms.

6.2 Airline C2 System

Plenty of research has examined SA in the aviation industry, particularly pilot's and ATCo's SA but little work has been done in AOC. One of the few studies that addressed SA in AOC (Bruce, 2011) has categorized SA into three levels (see Table 4). The first level, referred to as elementary SA, is usually gained at the commencement of the shift when controllers familiarize themselves with the state of the network, passenger loads, and weather. This is usually done through a staff briefing followed by an observation of the flight displays (Figure 8). The second level, referred to as core SA, goes beyond the first level in the sense that controllers identify categories that could provide a more enhanced level of awareness and anticipate potential disruptions. Controllers at this SA level look for turnaround times in short-haul flights and look for maintenance requirements and problems. Aspects like gaps, spar aircraft, maintenance restrictions, and late running operations are considered. The third SA level, referred to as advanced, enable controllers to identify more critical and complex aspects that could affect certain flights such as identifying regulatory restrictions (e.g. curfew hours); focusing on critical operations; and proactively searching for likely solutions. At this level, controllers seek additional information through communicating with various stakeholders to develop their SA. Finally, controllers at the AOC centre also develop team situation awareness thanks to a shared display which contains information about disruptions.

The importance of situation awareness has been explained in terms of being well informed, achieving enhanced readiness, being able to reduce operational errors, and predicting operator competence in complex environments (Bruce, 2011). An airline C2 environment is constantly evolving and therefore it is considered that achieving SA is a prerequisite for good decision making. There is no double that acquiring precise and complete information at the right time leads to well informed decision-making. This can sometimes be a challenge in AOC when controllers have to make decisions with incomplete information. This complexity creates a high level of uncertainty which may be complicated by conflicting information from different sources.

Table 4: Different situation awareness levels in the airline C2 system (Bruce 2011)

Situation Awareness Levels in AOC	Category
Elementary	● General overview of the network ● Passenger loadings ● Wait for disruptions to occur
Core	● Aircraft schedules and patterns ● Gaps between flight ● Maintenance requirements ● Crew connections and duty limitations ● Minimal passenger tranship times
Advanced	● Regulatory constraints ● Market conditions ● Potential Weather problems ● Potential for change/flexibility ● Critical operations

Figure 8: A printout of the screen image at 06:55 Coordinated Universal Time (see top horizontal UTC time-scale). A secondary horizontal time-scale showed local time (UTC C 9 hours). The horizontal blocks (called puks) represent the flights and include relevant information such as the flight number, actual passenger loading, departure and arrival airport, and departure and arrival time. The background color of each flight block was designed to represent a type of aircraft (a darker block represents a large aircraft and a light block represents a medium sized aircraft. The longer the flight duration, the larger the size of the block. The vertical axis on the left side shows the aircraft registrations that identify each aircraft in the fleet.

7. Operational Uncertainties

Both the railway and airline C2 systems are subject to a multitude of uncertainties with different levels and types. Sonenshein (2007) defines uncertainty as a "lack of information that makes constructing a plausible interpretation about a situation difficult." Information can be either missing, unreliable, or ambiguous or complex to process. Such uncertainties can significantly affect decision-making and lead to significant variations in the timetable of both airline and railway operations which can propagate through the network. This section provides an overview of uncertainties in both systems.

7.1 Railway C2 System

External factors can cause operational uncertainties that can vary from small deviations from the timetable (disturbances) to large deviations, in which the rolling stock and crew are rescheduled and long train delays and cancellations of services can be expected (disruptions) (Ghaemi, Cats, & Goverde, 2017). Examples of operational uncertainties that are relevant in the railway C2 system are listed in Table 5 (Golightly, & Dadashi, 2017; Marinov, Şahin, Ricci, & Vasic-Franklin, 2013).

Table 5: Examples of Railway C2 Uncertainties

Domain of Uncertainty	Example of Uncertainty
Environment	● Weather (Fog, wind, snow, leafs etc.) – impact on train driver and infrastructure ● Temperature – impact on infrastructure ● Power outage ● Objects, animals or people near or on the tracks ● Fatality ● Accidents
Train Stations	● Station overrun: crowd control after large public events or rush hour ● Track capacity ● Yard capacity ● Turnaround time (combining or dividing wagons)
Trains	● Technical failures ● Capacity issues in rolling stock leading to transport fewer passengers
Infrastructure	● Switches ● Tracks ● Overhead line dewirement ● Speed restrictions due to maintenance work
Crew	● Misconnect violation, rest violation, duty limit violation ● Crew no show
Passengers	● Delayed connecting passengers ● Passenger loading
Operators	● Human error
Traffic control/management system	● System failure

7.2 Airline C2 System

Because of the complexity of the airline C2 system, airline controllers are continuously confronted with many operational uncertainties ranging from potential weather problems, through aircraft repair time, up to crew and passenger related problems. These uncertainties when coupled with inadequate information can create significant hazards with important economic consequences on the airline. It is therefore of paramount importance that airline controllers are prepared for different states of the environment as we live in a stochastic world. Table 6 provides examples of uncertainties in the airline C2 system.

Table 6: Examples of Airline C2 Uncertainties

Domain of Uncertainty	**Example of Uncertainty**
Environment	● Weather related: Low visibility due to fog, wind, thunderstorm, snow. ● Accidents (e.g. bird strikes, lightning strike, animal on runway)
Airport	● Turnaround time (Cleaning, baggage handling, fuelling, etc.) ● Security threats ● Runway closure
Aircraft	● Technical failures ● Variations in maintenance procedures ● Safety checks
Crew	● Misconnect violation, rest violation, duty limit violation ● Crew no show
Passengers	● Delayed connecting passengers ● Embarking/ Disembarking times
Operators	● Human error
Air Traffic Control	● ATC restrictions ● ATC system outage

8. Recovery Strategies

When disruptions occur operators at the airline and railway control centers adjust in real-time the operations by selecting and implementing the best possible actions. This section provides an overview of different actions taken by the operators to manage disruptions along different problem dimensions.

8.1 Railway C2 System

Table 7 discusses a number of actions that can be taken in the occurrence of a disruption, in which the issues needing to be fixed are related to the physical infrastructure, train, crew or passengers.

Table 7: Possible recovery solutions in a railway C2 system

Problem Dimension	Possible Actions
Physical railway infrastructure (e.g. switch, powerline, track)	• Fix infrastructure • Use infrastructure with certain procedures (maximum speed driving) • Implement a disruption mitigation procedure that consists of a set of specified actions for trains in a specific geographical area
Train	• Exchange train • Fix train • Lease train • Reroute train • Cancel train • Delay train
Train driver and conductor	• Use crew at train station • Use nearest crew to train station • Exchange crew from other trajectories • Seek extensions to crew duty time • Use crew with free time • Position crew to other train stations (deadheading) • Delay crew for signing in duty • Use crew with vacation/ day-off • Proceed without crew • Propose change of rolling stock • Accept delay/ await crew from incoming train • Cancel train
Passengers	• Arrange alternative transportation (e.g. bus between stations)

When a disruption causes a strong limitation in the use of the railway infrastructure, it is required to scale down the frequency of trains and run according to an adjusted timetable. Many countries make use of these predefined solutions or contingency plans to assist traffic controllers. The process involves scaling down the timetable as fast as possible so that trains are not stacking up the network, taking extra time to retrieve and causing inconveniences to passengers. The alternative timetable runs accordingly in the second phase, while the third phase involves increasing the frequency of trains and returning to the original timetable. Figure 9 depicts the process. In managing the disruption, crew rescheduling has been often considered as the most difficult to handle (Abbink, Huisman, & Kroon, 2018). The issue of crew rescheduling becomes especially complex when train drivers have a diverse schedule that does not allow them to go back and forth on the same route, which is the case in the Netherlands.

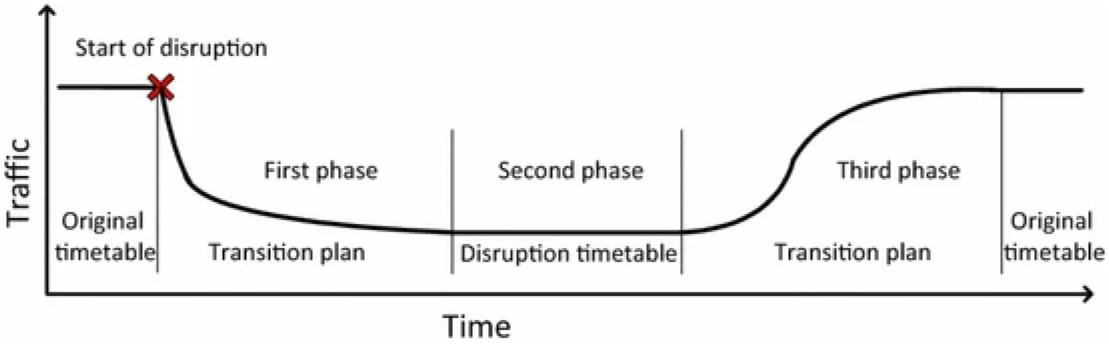


Figure 9: The so-called 'bathtub' model that resembles the traffic level during disruptions (Ghaemi, Cats, & Goverde, 2017).

8.2 Airline C2 System

When disruptions occur operators at the AOC centers adjust in real time the fight operations by selecting and implementing different actions. These actions aim to recover the flight schedule, and solve the aircraft, crew, and passenger problems (see Table 8).

Table 8: Possible recovery solutions in an airline C2 system

Problem Dimension	Possible Actions
Aircraft	• Exchange aircraft • Combine flights to free up aircraft • Delay flight • Ferry aircraft from nearby airport • Lease aircraft • Request high cruise speed to compensate for delay • Reroute flight • Cancel flight
Crew	• Use crew at airport • Use nearest crew to airport • Exchange crew from other flights • Seek extensions to crew duty time • Use crew with free time • Position crew to other airport • Delay crew for signing in duty • Use crew with vacation/ day-off • Proceed without crew • Propose aircraft change • Accept delay/ await crew from inbound aircraft • Cancel flight
Passengers	• Rebook pax. to other flight at own airline • Rebook pax. to other flight at other airline • Keep pax. on delayed flight

9. Workflows

This section provides an overview of current workflows for various types of disruptions and illustrates communication flows and coordination between operators which is key to system resilience.

9.1 Railway C2 System

When infrastructure capacity in a geographic area becomes very scarce to unavailable for a longer period due to a disruption, a contingency plan is selected by railway and passenger control to efficiently and effectively implement a new timetable. Figure 10 depicts an example of a workflow from the moment an issue has been notified and a large disruption in the train traffic flow is expected. Multiple operators are individually informed and updated by telephone. The workflow also shows that operators are sometimes informed twice due to communication within and between organizations. Network controllers are able to assess a disruption log system in which status updates are given. Apart from this disruption log system no other supporting systems are available that aid in the management of the disruption.

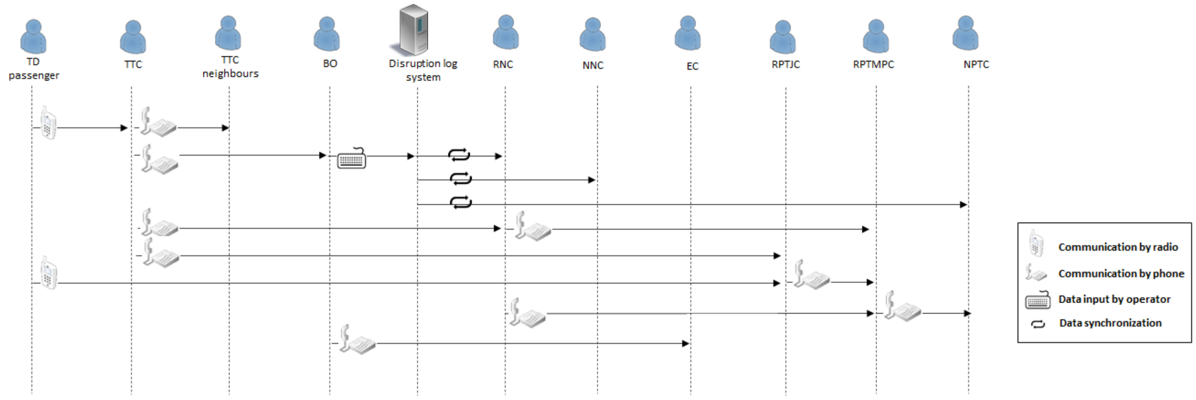


Figure 10: Example of the workflow in the first stage of a disruption

Figure 11 depicts the overall communication and coordination between railway and passenger traffic controllers in a simulation study who are faced with a large disruption in the network (Lo & Meijer, 2020). In the simulation, a malfunction in an engine causes the train to smoke, leading to the clearance and unavailability of multiple tracks at a station.

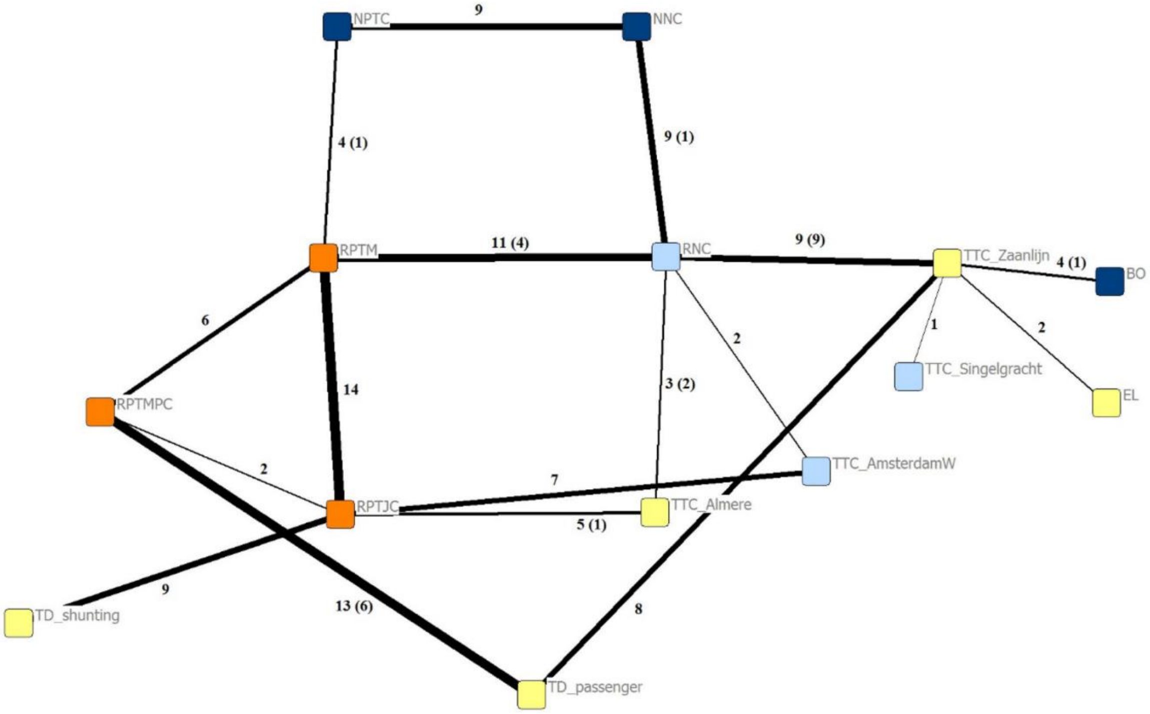


Figure 11: Communication flow in a disrupted scenario (Lo & Meijer, 2020)

Social network analysis has been applied to the communication flow to assess the centrality of certain operators in the network, e.g. which operator is mostly in contact with other operators in the network, which operators is most efficiently obtaining information and which operator is difficult to contact. Findings show that when a disruption occurs the TTC acts as a gatekeeper of information in the network between several subgroups via telephone. Additionally, the RNC has many lines of communication to exchange information. The findings also show that co-location facilitates an increase in communication, which is unaffected by failed or unresponsive calls.

9.2 Airline C2 System

Airlines have established procedures and workflows for managing different types of disruptions. Figure 12 gives an example of workflow at a major airline upon detection of an aircraft mechanical problem. Specialist agents have access to different information platforms including the Aircraft Movement System and the Crew Tracking System. As soon as a disruption is reported, they will be notified immediately and start resolving the problem. Figure 13 visualizes the communication flow between different agents involved in disruption management. The figure illustrates that information is conveyed by means of radios, telephone calls, and using online systems connected to the airline network. While these procedures help controllers in the event of familiar disruptions, they could pose a challenge in case of a disruption that was not encountered before.

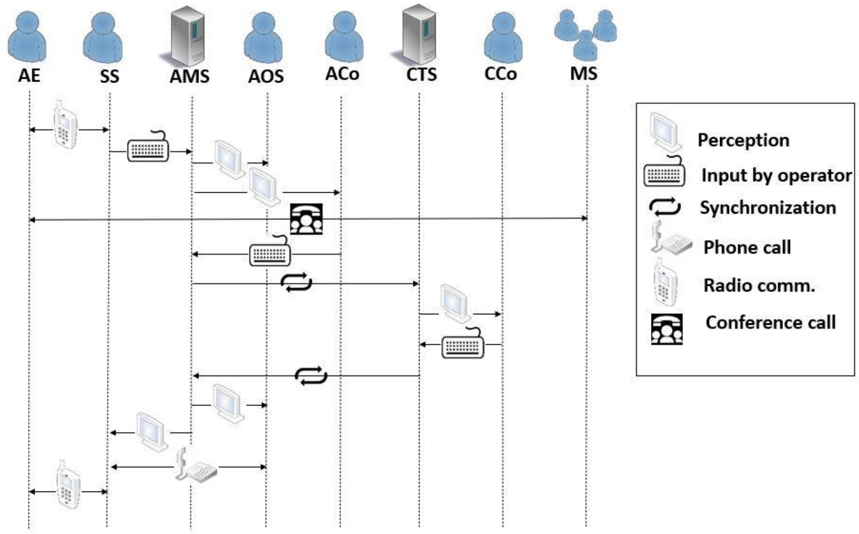


Figure 12: Example of an airline disruption management procedure upon detection of an aircraft mechanical problem

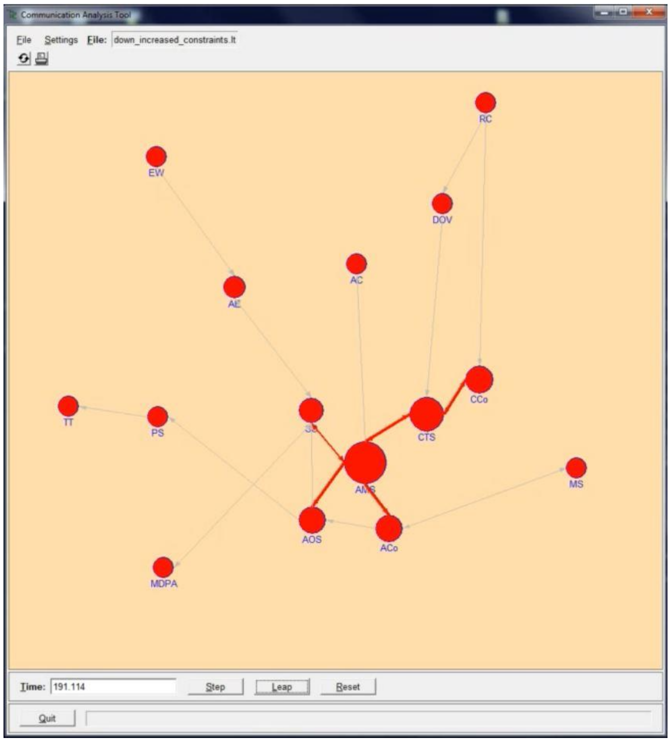

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Figure 13: Example of communication flows in an airline C2 system during disruption management. Analysis performed using LEADSTO simulation tool

10. Evaluation Results

This section reflects on the descriptive analysis that has been conducted in Sections 3 to 9 for both the railway and airline C2 systems. Table 9 shows both similarities and differences between the two domains. The following subsections provide an elaboration on the identified similarities and differences for each component.

Table 9: Similarities and differences between the railway and airline C2 systems

Component	Similarities	Differences
Purpose	• Similar objectives and performance areas such as safety, punctuality, efficiency and customer satisfaction • Issues in competing values	Performance indicators are set by the international organization ICAO (airline) versus national government (railway)
System phases	Similar strategic plans to 1) attend to the growth in demand and the need to increase traffic flow by increasing the number and frequency of transport, 2) making use of digital (and smarter) systems	Different use of terminology: tactical in railway is different than in airline.
Structure	Similar structure in terms of network manager and transport operating company (airline, train operating company)	Multiple regional control centers and one national integrated control center (railway) versus one integrated control center (airline)
Situation Awareness	• Role of monitoring for situation awareness • Use of shared displays for team situation awareness • Communication and coordination important for situation awareness development	Passenger loadings is an important factor in airline
Uncertainties	Many similar uncertainties	Disruptions due/on/around the infrastructure play a big role
Recovery Strategies	• Many similar problem dimensions (aircraft/rolling stock, crew, passengers) • Dominant issue in disruption management is rescheduling of rolling stock and crew?	Different procedures used amongst in airline, single contingency plan in railway
Workflows	A select number of operators function as central nodes in the network	Airline makes more use of supporting systems for disruption management

Purpose

The comparison of both railway and airline C2 systems shows that both systems share the same purpose, mainly ensuring that operations adhere as closely as possible to the published schedule in a safe manner. Similar values include network safety, punctuality, efficiency, and customer satisfaction. Competing values are an issue in both C2 systems. Dissimilarities can be found in the way of focus of the C2 systems, i.e. railway predominantly short-haul (national) train services, airline short-haul to long-haul international flight services.

System Phases

Strategic plans in both railway and airline C2 systems are focused at facilitating a growing demand of flights and train services, next to further steps in digitization. While the aviation sector already makes use of highly standardized systems, the railway sector needs to take further steps in digitization as currently being done with the standardized ERTMS safety system. While the use of decision-support systems is still very novel for railway, airline C2 systems already make more use of this with future plans to further develop more advanced airline C2 systems.

In terms of timetable or schedule development similar phases are used, apart from the different terminology in tactical and operational phases. Within the railway differences are also perceived, in which passenger traffic control also further differentiates the operational phase into operational and short-term planning. All in all, the similarity is that disruption management involves operators who focus on real-time adaptations of the timetable, and the schedule of crew and rolling stock/aircraft.

Organizational Structure

Both railway and airline C2 systems have established well defined roles for different agents to manage disruptions. Specialist agents manage various problems according to their expertise and assist their supervisor who oversees disruption management. One difference that can be noticed in the organizational structure is the fact that the railway C2 system has multiple regional control centers in addition to the main operational control center, whereas the airline has only one major operations control center. This center is often supported by the Hub Control Center which is usually located near the airport.

Situation Awareness

Controllers in both systems are notified about disruptions either by human operators or observing their shared or individual displays. It is therefore important to maintain situation awareness to reduce operations errors as both environments are constantly evolving. This can be achieved through monitoring operations through the control system and forecasting/ proactively preventing potential problems as much as possible before they occur. An interesting finding was that in both systems situation awareness can be maintained at different levels. The first level, usually gained at the beginning of the shift, aims at having a general overview of the network (departure, destination, planned routes). In the airline C2 system, there is also an interest in passenger loadings. The second level focuses on train and aircraft schedules and patterns and aims at identifying potential disruptions that could arise. The third level aims at seeking detailed information concerning the infrastructure and assets such as the status of switches, signals, maintenance, etc. This level allows controllers identifying complex aspects that could affect the network. The comparison also reveals that both systems make use of shared displays to enhance team situation awareness. In addition, communication and information exchange plays a significant role as well when managing disruptions.

Operational Uncertainties

Both railway and airline C2 systems are subject to various operational uncertainties which can have a significant impact on operations. A typical example in both systems is bad weather, which can negatively affect operations and induces ripple effects propagating throughout the airline or railway network. Another example is that of a malfunctioning aircraft or train being stuck with its passengers at a distant location, as a result of which all passengers will experience significant delays. Also similar issues in rescheduling of aircraft/rolling stock and crew are experienced in both C2 systems.

The main dissimilarity in operational uncertainties between the airline and railway C2 system lies in its operational consequences. Disruptions are largest for airline C2 systems when an aircraft is unable to land or take-off. Disruptions are largest for railway C2 systems when physical railway infrastructure is limited and trains cannot reach their destination. The impact of the operational consequences are higher for the airline C2 system, where trains can be rerouted or alternative means of transportation can be offered (e.g. by bus or taxi). For airline C2 systems alternative means of transportation would cause a large delay in passenger travel times or are no option at all.

Recovery Strategies

Many similar parallel recovery strategies can be identified between the railway and airline C2 systems in terms of possible actions for their crew and the aircraft/rolling stock. An identified difference between recovery strategies is in terms of the disruption mitigation procedures. In the railway C2 system a predefined solution or contingency plan is chosen based on the cause and location. As these plans are developed beforehand no further negotiation is needed between operators from different organizations. For rail disruption management this means that a solution can be implemented as soon as this is known, therefore stopping a ripple effect of train delays or stranded trains throughout the network is therefore stopped.

Workflows

In order to structure the communication and coordination between operators and manage different types of disruptions, operational workflows have been established. When disruptions occur, controllers work according to the established procedures for the specific types of disruptions (e.g. fire in a tunnel or broken aircraft an outstation). Though the nature of problems might be different in both domains, coordination between operators remains key in both domains to resolve problems. An observed similarity is that there are a few operators who function as central nodes in the network, while an observed dissimilarity is that the airline C2 system has support systems to aid in the disruption management, such as an Aircraft Movement System and the Crew Tracking System.

11. Discussion & Conclusion

Airline and railway C2 systems are complex socio-technical systems. They both comprise numerous facilities, operators, processes, and technology. They are both embedded in a large network of other complex socio-technical systems including airports, ATC centers, and train stations. Technology plays a central role in both systems as does the social context within which the systems are operating.

The descriptive analysis in this paper has identified similarities in both C2 systems, especially with regards to the purpose, system phases, operational uncertainties and workflow. Both railway and airline C2 systems share similar overall objectives, identify a growth in transportation demand that would require a system redesign, identify a number of similar external factors that cause operational uncertainty such as the influence of weather and absence of crew, and show that a few operators are a central node in the operational network. A number of components have yielded insights in differences between the C2 systems. For instance, the comparison showed that recovery strategies differ where one contingency plan is applied in the railway C2 system to manage a disruption. In terms of organizational structure, the railway C2 system is organized into multiple regional control centers opposed to one main control center in the airline C2 system. In terms of performance indicators a large difference is that international organizations are defining this for the airline C2 system and a national government for the railway C2 system. Additionally the airline C2 system makes more use of support systems, although the use of shared displays is common in both C2 systems. All in all, the current study provided insights into the two socio-technical systems, in which especially the differences can provide guidelines for improvement of C2 systems.

As this type of complex systems is characterized by a large number of interconnected parts, the difficulty to predict the behavior, and the existence of many different stakeholders who might necessarily share the same viewpoint on performance. In (Shah et al. 2005), it is well explained that the key difficulty of evaluating complex systems is to address their emergent behavior. A promising approach to identify emergent behavior is ABM as it has been extensively used to a) analyze complex socio-technical systems (Bouarfa et al. 2013) and b) address cases where agents need to collaborate and solve problems in a distributed fashion.

A limitation in this study is that the current research has been assessed based on research and knowledge of C2 systems in a few countries. Especially the railway C2 system was based on the Dutch rail and passenger traffic operations. Comparisons with other countries need to be included.

Future work could focus on including more research on other subsystems within the aviation and railway C2 system, e.g. ATC, airports, shunting yards. Other future work could also expand with other socio-technical components that are needed for ABM, such as the level of system automation and detailed situation awareness development of an individual operator. Also it would be valuable to delve deeper in the consequences of certain socio-technical components, such as how competing values are dealt and what their impact is.

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