Learning lessons in resilient traffic management: A cross-domain study of Vessel Traffic Service and Air Traffic Control

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Abstract

Although younger than the maritime domain, aviation has had a huge impact on the system design and development within shipping. Stakeholders often look towards aviation to make shipping, and the way that traffic is handled and organised, safer, more efficient and more effective. Although legally not the same, Vessel Traffic Service (VTS) is frequently compared to Air Traffic Control (ATC). In this article the area of traffic management within the maritime and aviation domains is addressed from a Resilience Engineering perspective. Focus is placed on the arrival part of a mission. The comparison is based on information collected during two study visits at VTS centres and one study visit at an ATC centre. The two organisations are described with the help of the Resilient Engineering capabilities: to respond, to monitor, to anticipate, and to learn. Furthermore, it is discussed how VTS and ATC adapt to cope with the complexity encountered during daily work.

Introduction

For the past 40 years advancements in technological and organisational design within the maritime domain has been highly influenced by developments within aviation. In particular, when discussing aspects of traffic management and traffic safety, the aviation domain is often cited as one of the predominant examples for safe and efficient traffic movements (e.g. National Research Council, 1994; van Erve & Bonnor, 2006; Österlund & Rosén, 2007). Although cross-domain studies between the maritime and the aviation domains are often encouraged, there is a lack

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of research in the area of traffic management concerning the two responsible organisations, Vessel Traffic Service (VTS) and Air Traffic Control (ATC). This paper attempts to address this gap in the research in order to enrich and inform the overall debate on system design within traffic management. Resilience Engineering (RE) concepts are used to highlight normal operation and the way systems adapt to, deal with, and compensate for anticipated and unanticipated events.

This article does not present a full comparison of the two systems, but rather aims to increase the understanding of the similarities and differences within the systems. As VTS is mostly provided in port approaches, this article concentrates on the arrival phase of a mission for both ATC and VTS operations.

Air Traffic Control (ATC)

The primary function of an ATC service is to promote the safe, orderly and expeditious flow of air traffic (Nolan, 2010) between the origin and destination airports. ATC was introduced when aircraft became faster and started flying at high altitudes, making Visual Flight Rules insufficient. Today, aircraft fully depend on ATC. The entire ATC system is based on a highly structured network, which is governed by precise rules, procedures and highly reliable communication links (Marine Board, 1996).

In most countries airspace is divided into controlled and uncontrolled airspace. ATC is responsible for ensuring that minimum separations are maintained between aircraft within controlled airspace by issuing a series of heading, altitude and speed clearances. ATC has authority in controlled airspace whereby flight crews are required to follow all instructions during normal flight operations[1]. In addition to these instructions, ATC provides meteorological and navigation information and Notices to AirMen (NOTAMs).

Vessel Traffic Service

The primary function of Vessel Traffic Service is to provide an information and assistance service to commercial maritime traffic within channels, port approaches, or other areas that are difficult to navigate in. In comparison to ATC, VTS is always a local service, and can only play a role in territorial waters. VTS is implemented locally but within an international framework (IALA, 2008). The local implementation leads to differences in service level and service provision (Praetorius, 2012). There are three different service types which a VTS can offer: Information Service (INS), Traffic Organisation (TOS), and Navigational Advice and Assistance (NAS). INS provides information to all participating vessels within the VTS area, e.g. hydro-meteorological and traffic information. TOS is concerned with the traffic operations: e.g. allow manoeuvres, block access or set speed limits. NAS provides information for the navigation, e.g. own position relative to obstacles (IMO, 1997).

[1] In emergency situations the pilot in command has final responsibility for the safety of the flight and may deviate from ATC instructions.

Ships do not depend on VTS for their safety. They are themselves responsible for collision prevention. As such, VTS neither gives instructions nor has authority except in safety-critical situations. This is due to the historic split between ship and shore services, which assigns all liability-related issues to the Master of the vessel, meaning that he or she is the one who makes the final decisions on navigational matters.

Table 1 shows an overview over the two domains and highlights the services' basic structure. One can easily see that the systems differ largely in dimensionality, speed, environment, traffic density, flexibility, and consequences of collisions.

Table 1: Comparing ATC and VTS basic constituents

	ATC	VTS
Dimensionality	Movements in 3 dimensions	Movements in 2 dimensions
Speed	500 Mph	~20-30 knots
Environment	Empty	Restricted (islands, reefs, etc.)
Density	High (aerodromes), low (cruise, transocean)	High (port approaches), low (oceanic)
Flexibility	Limited, speed must be maintained	High, vessel can be slowed down or stopped
Consequences of collision	Fatal, even slight mid-air collisions	Ranging from minor to fatal

Although both systems show large differences in their basic structure, they both are responsible for promoting the overall goal of safe, fluent and efficient traffic movements. Both services focus on providing information in complex domains with autonomous vehicles that depend on external support for their navigation. The operations normally deal with non-linear interactions under high stakes.

Cross-domain studies of VTS and ATC

There is a sparse amount of research addressing both VTS and ATC and the appropriateness of comparisons between the shipping and aviation domains. The following paragraphs will summarise this previous work and introduce why an analysis considering RE could be of benefit.

As emphasised by van Erve and Bonnor (2006), VTS and ATC are most similar on the level of goals and objectives for the services. Both services are introduced to increase traffic safety and fluency, support the crew in avoiding collisions with other traffic and obstacles, and to provide voyage-relevant data. However, the two traffic services have been designed in different ways. Whilst VTS was introduced rather late into the shipping domain and developed as an add-on to the port to compensate for efficiency and effectiveness issues of sea transport, ATC was a necessity for the aviation environment and as such developed into a structure fully embedded into aviation.

Another issue for cross-domain studies of ATC and VTS is the overall control setting within the domains. Whilst ATC is built upon centralised control exercised by an air traffic controller (ATCo), VTS is organised as a distributed system, in which the vessel autonomously acts on the information that the VTS operator (VTSO) feeds into the traffic system via VHF radio (van Westrenen & Praetorius, 2012). ATC and VTS each control traffic systems of largely autonomous vehicles. They represent two forms of traffic management: a distributed system and a centralised one. Considering the similarities and differences, Anderson (1991) argued that ATC and VTS comparisons may not always be useful, but can be used as an interesting base for reasoning about possible developments. One such possibility described by the National Research Council (1994) was the development of a Vessel Traffic Control (VTC) model, in which aviation domain concepts are applied to maritime settings; however, the council noted at the same time that the adaption of such a VTC would require fundamental changes in how the relation between ship and shore is regulated today, something it considered not feasible.

Resilience Engineering

Resilience Engineering (RE) is a discipline that strives to understand how large socio-technical systems cope with the complexity of daily operation. The focus is on examples of the positive, meaning that resilience is concerned with how a system succeeds by adapting its performance to the demands of the environment, not on a failure to do so (Hollnagel, 2006). As such, safety is an emergent property, which arises when the system balances goals and demands successfully (Woods, 2006). The system adjusts its performance to the demands of the environment, which enables it to achieve its goals under a large variety of operational conditions (Hollnagel, 2011). Within the VTS and ATC domains efficiency and safety are the primary goals that need to be balanced by the organisations.

There are four basic *system capabilities* that a system needs to possess in order to be resilient: it must be able to *learn* from past events; to *anticipate* future opportunities, challenges and demands; to *monitor* the environment and its own performance for possible threats; and to *respond* to regular and irregular situations during daily operation (Hollnagel, 2011). As Woods (2006) notes, all systems are both resilient and brittle. The degree of resilience and brittleness determines whether a system is capable of dealing with a large variety of conditions and how this in turn affects the system and its performance. Furthermore, Woods (2006) emphasises that monitoring and managing the degree of resilience depends on four *system properties*: the system’s buffering capacity, its flexibility, its performance margins, and tolerance towards disturbances. VTS and ATC will be compared on these aspects.

Study visits

Study visits were conducted to two full-mission VTS centres and one ATC Approach centre in order to get a basic understanding of the working conditions and the systems' functioning in both domains.

Both VTS centres were part of medium-sized European ports and offered all three service levels. The ATC Approach centre visited is responsible for the Terminal Manoeuvring Area surrounding a medium-sized European airport. The centre offers full ATC service for commercial and general aircraft operating between 3000ft and Flight Level 095. The airspace is used by aircraft operating both to and from the airport, and aircraft transiting through the airspace.

The aim of these visits was to enhance the domain knowledge and to obtain information on how the operators in the centres deal with a variety of situations encountered during normal operations for the arrival phase of a mission, including understanding how the services offered by the organisations are realised in varying environments, and how the operators relate their actions to the operational short-term and long-term goals of the organisation.

Results and analysis - Resilience in the VTS and ATC domains

The following paragraphs present how concepts of RE relate to the system design of ATC and VTS.

The main functions of the systems

ATC is legally a traffic management system, whilst VTS is currently implemented as an assistance service, or "an information node for seafarers" as stated by the National Research Council (1994). Whilst ATC is entitled to give direct orders, the decision-making within the maritime domain remains on-board. Based on the basic settings, there are four functions to guarantee the safe and fluent movement of the traffic in both domains: monitoring the state of the traffic participants, ensuring their separation, routing them, and planning the overall capacity for the area under surveillance. Table 2 gives an overview of the functions and describes who is responsible for initiating them within the ATC and VTS domains.

Table 2: Main functions for traffic safety and fluency

Function	ATC	VTS
Monitoring state	ATCo	VTSO & participants
Ensuring separation	ATCo	Traffic participant(s)
Routing participants	ATCo	Traffic participant(s)
Capacity planning	ATCo/ANSP (Air Navigation Service Provider)	VTSO (limited degree), mostly pilots & participants

Table 2 displays the four main functions that ensure the safe and fluent movement of traffic within a designated area, in the case of this article the arrival phase of a voyage. Within the ATC domain the ATCo is primarily responsible for the majority of decision-making regarding traffic management (i.e. the speed, altitude and heading of the aircraft). The ATCo issues clearances to ensure correct separations are maintained; monitors the effects of instructions on the state of the aircraft; can decide to route or re-route traffic participants; and he takes the responsibility for the overall capacity planning of traffic in the area.

In comparison to the aviation settings, the VTSO does not have any mandate to actively steer or route the traffic. Therefore, only monitoring and capacity planning, to a limited extent at least, are within the responsibility of the VTSO. Separation to other traffic participants, as well as routing and re-routing of a vessel are the responsibility of the Master. The pilot service supports the safety and fluency of traffic movements. The available capacity of an area is often limited by the availability of pilots and services.

Resilience capabilities within ATC and VTS

There are four main capabilities (learn, monitor, respond, anticipate), which a system requires in order to maintain operation under anticipated and unanticipated events. Table 3 summarises how these capabilities manifest themselves within the ATC and the VTS domains.

Table 3: Resilience capabilities within ATC and VTS

	ATC	VTS
Learn	Reactive Proceduralised Centralised	Seamanship/experience from both sides Local needs Interpersonal learning amongst operators
Monitor	Hierarchical Objective measures Expertise	Individual Objective/subjective measures Experience & expertise
Respond	Procedures Upward delegation Discretion of ATCo (to some extent)	Experience
Anticipate	Capacity planning Weather planning	Berth planning Pilot service cooperation

Learn

Learning within the ATC domain is largely reactive based on standardised reporting structures and mainly focused on what went wrong. Furthermore, as there are international procedures for how a service is provided, the learning is almost solely procedural and centralised at a state or country level. This is in contrast with how learning takes place within the VTS domain. Within this domain, although there are international guidelines, learning within the organisation is the responsibility of the national administration, often with heavy focus on local knowledge, leading to differences in operator training and in how services are provided. Additionally, good seamanship (rules about safe and reasonable behaviour at sea) and experiences as an active seafarer and as a VTSO are essential for the learning, especially when it comes to learning from positive examples, not only from accidents.

Monitor

Monitoring is a critical element of ATC, particularly for the Arrival and Approach function where aircraft are closely spaced (compared with the en-route environment) and are subject to frequent speed and altitude changes. Controllers must be able to monitor traffic situations that change on a very short timescale (for example, an aircraft pair can start to lose separation very quickly if one aircraft does not respond correctly to a speed instruction). It is therefore essential that controllers continuously monitor the traffic situation using equipment and data that updates in sufficient time for them to respond to emerging situations. This is primarily achieved using both primary and secondary radar systems (including transponders and ADS-B) which are updated every few seconds.

VTSOs identify traffic monitoring as one of the most essential tasks of their work as it is a precondition to be able to provide any kind of service level to the participating vessels (Praetorius, 2012). During the monitoring task the VTSO uses integrated radar and Automatic Identification System (AIS) information, as well as the VHF communication and databases at hand to obtain information on the traffic and its movements and intentions. The vessels' inertia leads to a significantly slower system, but this is largely compensated for by the close proximity ships operate in.

Monitoring also highlights the importance of *knowing what to look for*. In both domains the study visits showed that the operators base their judgements heavily on their experience as a traffic monitoring entity and their overall expertise within the domain. Situations are identified as normal or abnormal based on how the traffic frequently behaves (Praetorius, 2012).

Respond

The ability to respond quickly is critical within the ATC domain given the short timescales involved. This is important on both organisational and individual levels. An Air Navigation Service Provider (ANSP) must respond very quickly to unexpected disruptions in operations (e.g. technical failures, accidents, and atmospheric disturbances). Some require responses in seconds, others in hours, and may range from individual decisions to a complete reorganisation of the system. Because of the different timescales and extent of the effect, controllers may not always be able to follow a standard procedure and may have to rely on intuition and past experience. For example, an ATCo can choose to remove an aircraft from following a standard published arrival route and initiate tactical radar-vectoring, increasing capacity and flexibility at the cost of workload and complexity. It is the decision of an individual controller when to start radar-vectoring an aircraft, which introduces a lot of normal variability into the system.

The ability to respond is equally important for a VTS operator. When the situation changes significantly he must inform all ships affected. It is the responsibility of the VTSO to ensure that all ships adapt to the new situation. Although the vessels do not travel with the same speed as aircraft, response times in the VTS domain can also be a matter of seconds depending on the manoeuvring capabilities of the traffic participants in the determined area. Further, as there are no or only a few objective measures for monitoring the traffic movements, responding relies heavily on the individual operator and his/her prior experience as a seafarer rather than, as in ATC, being dependent on standardised procedures.

Anticipate

The most important aspects of anticipation within the ATC domain are capacity and weather planning. These two factors determine how traffic will be handled and ultimately managed by the operator, e.g. splitting a sector into minor control areas. An ATCO has access to comprehensive information concerning all aircraft that will enter his/her sector within a given timeframe, which includes the planned altitude, speed and route followed by the aircraft. Furthermore, the ATCo needs to constantly anticipate deviations that may occur within the system (normal and unexpected). A deviation may be the result of a flight crew not complying with an issued clearance, a missed approach to land or an emergency developing on-board an aircraft. There are several warning tools that help the ATCo to identify potential problems, such as the Short Term Conflict Alert (STCA) tool, which predicts a potential loss of separation between an aircraft pair.

Anticipation within the VTS domain is very limited. Since VTS cannot control the vessel, VTSOs tend to keep their planning horizon short. Ships report at the border of the VTS area. Monitoring starts from there. Some tools, such as automated Closest Point of Approach (CPA) calculations, can be used but their effectiveness is limited. Anticipation is largely based on extensive experience, not on the process, procedures, or tools. An airport’s capacity for handling aircraft is more than ten times higher than ports handling ships.

System properties

Due to the contrasting ways that the ATC and VTS systems are organised, the largest differences are observed when comparing the system properties (Table 4).

Buffering capacity

ATC operates with a focus on traffic capacity. By allocating flight levels, routes, and creating holding areas, control can constantly balance availability and demand. Planning assures optimal use of the capacity and the buffering assures that sufficient spare capacity is available should a critical situation develop.

Within VTS, buffering capacity is realised by the ships autonomously. Only when traffic becomes dense, or when delays become too long, ships can be directed towards an anchorage area. Buffering capacity is available in the navigable water, but it is not planned for as planning is often restricted to berth allocation.

Table 4: Resilient system properties

	ATC	VTS
Buffering capacity	Flight levels Speed constraints Routes Holding Full planning	Ship domain Free sailing Anchorage Some planning
Flexibility/stiffness	Sector boundaries Routes	Highly flexible due to lack of sailing structure
Performance Margins	Separation Throughput Weather	Minimum CPA Hull clearance Hydro-meteorological information
Tolerance	Brittle	Some grace

Flexibility

ATC is a rather inflexible system due to the highly organised structure. Sector boundaries and routes are fixed, flight levels allocated, control areas sharply defined, and arrivals and departures fully procedural. VTS is highly flexible. Very little is predetermined, and expertise is used to optimise traffic movements on an individual level, based on experience.

Margins

In the ATC domain, all safety margins are pre-set, guaranteeing a high level of safety. All traffic is well separated from each other within the environment. The margins are defined in space, time, speed, and all other variables decided to be of importance. In contrast, within the VTS domain, the margins are largely undefined. Only deep-draught ships have very specific safety margin requirements. Nevertheless separation largely remains an individual decision based on “good seamanship” (National Research Council, 1994). As a result, no safety level can be guaranteed beforehand, and risk assessment and handling remains rather pragmatic.

Discussion and conclusion

The analysis above has identified several similarities and differences within the design of traffic management systems in the shipping and aviation domains. ATC and VTS have been analysed with the help of RE system capabilities and properties.

The analysis reveals that although the systems share common goals, there are huge differences in how safety, or resilience, are realised within the domains. Within ATC, a high degree of standardisation impacts on the overall flexibility of the system. ATC is rather stiff in its design with clear performance margins and procedures that can help the system to cope with a variety of situations in which it needs to adapt its performance, e.g. splitting a sector during high traffic volumes. On the other hand, within the operational constraints, the system is very safe and efficient.

VTS, on the contrary, is a very flexible system that leaves the details of execution to the actors in a situation. There are no objective safety margins, and the overall lack of standardisation allows for a wide scope of responses that the system can draw upon whenever coping mechanisms are needed. However, whilst the system is able to handle a variety of situations with some grace, the open design and the lack of centralised control invites vessels to a high degree of local optimisation, which set the overall system's safety at risk as it can easily lead to disturbances on a system level, e.g. a ship blocking the fairway or the entrance to a lock. Whenever system disturbances occur, the entire traffic management needs to be re-organised, whilst at the same time the decision-making remains on-board, posing serious limits to the possible work of a VTSO. Furthermore, the lack of standardisation, technical-wise and organisational-wise within the VTS domain has consequences for how the system is accepted by those who are supposed to make use of it, i.e. the navigating officers (Nuutinen, 2005).

Lessons to be learned within system design become apparent when the two traffic management systems are compared. VTS could profit from more standardisation that carefully considers local conditions whenever procedures are stated. Furthermore, objective measures, such as separation minima, could be promising within shipping to guarantee a minimum level of safety.

Within the ATC domain, shipping and VTS specifically, can serve as a good example for how control can be exercised in a distributed system with autonomous players. VTS, due to its flexibility, can handle a variety of situations, in which local optimisations are ideally balanced with overall system optimisations. Ship and shore share control, which could be interesting to consider whenever concepts such as free flight are discussed. As previous studies have emphasised, the introduction of concepts such as free flight, will change the relationship between aircraft and controller (Hollnagel, 2007). Lessons that can be learned from VTS development might be a good source of inspiration when free flight scenarios need to be constructed. Both domains can profit from cross-domain knowledge to inform a safer design of future traffic management systems.

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