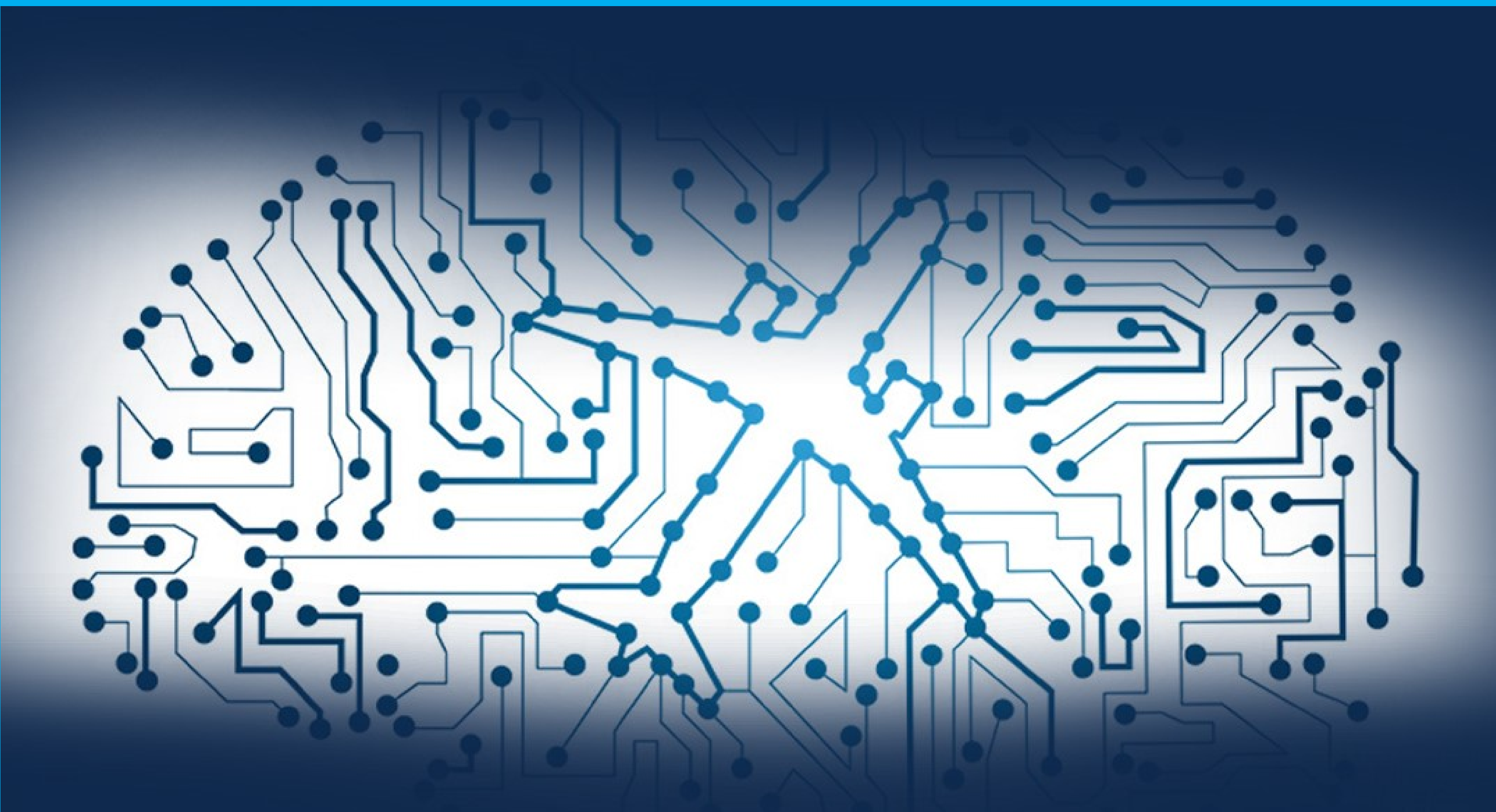
Common Ground in coordination

Mannat Kaur

Causes, Identification and Repair of loss of Common Ground in coordination in ATM



TU Delft

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by

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TU Delft

Preface

While the sheer magnificence of the aerospace industry has fuelled my passion for this field since childhood years, the extreme complexity and undefined nature of the human mind have now also captured my curiosity. When I came across this master thesis last year, I was sure that this was a project that I certainly wanted to pursue and make my very own (and very small) contribution in the field of aviation safety.

The past year has been the most challenging and also the most educational year of my academic career. Working on this master thesis has been quite a unique and delightful experience since the very beginning. Not only was I working on something I didn't have much background in but I was also actively trying to recognize how my thought processes flow. This was necessary to place myself in the required mindset to do research work on complex sociotechnical systems. None of this, however, would have been remotely possible without the guidance, support and insights from my supervisor, Dr. Alexei Sharpanskykh. I would like to extend my sincere gratitude to him for everything and would also like to thank him for helping me grow as a person. I also would like to sincerely convey my thankfulness to Professor dr. ir. Henk Blom for always providing his meaningful feedback and opinions that provided this master thesis with the level of elegance that I did not previously envisage.

It is now time to acknowledge those fundamental social elements that exist at the very basic level and give rise to this beautiful, undefined, unpredictable and complex reality that I experience as life; my friends and family. I am deeply grateful to Marco Bolognin for perfect common ground, to Srikar Yadala Venkata for complete situation awareness and to Arjun Puttabakula for excellent directability. I thank you for being actively present and ever-encouraging throughout this crazed journey. The final thank you is to, of course, my parents who have been my anchor since forever.

"We have a closed circle of consistency here: the laws of physics produce complex systems, and these complex systems lead to consciousness, which then produces mathematics, which can then encode in a succinct and inspiring way the very underlying laws of physics that gave rise to it."
Author: Roger Penrose

Mannat Kaur
Delft, February 2017

Abstract

Over a century has passed since humans took to commercial flying. Traditional safety practices have worked well but the last decade has seen the need for an updated understanding of ATM safety. The modern safety views are complementary to the traditional ones but are also a new way of understanding and enabling safety practices. This master thesis report presents a comprehensive review of the sources chosen from literature to better understand how a complex sociotechnical system, such as ATM, would operate. Certain selected coordination aspects will be the focus of this master thesis and will be used to model and analyse an ATM case. The ultimate aim of this research project is to add to the growing body of knowledge in the field of ATM safety, to make flying increasingly safer and to enable a complex system to be resilient.

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List of Abbreviations

ATM .... Air Traffic Management

STS .... Sociotechnical system

ABM .... Agent-based model

MAS .... Multi-agent system

MASA .... Multi-agent situation awareness

CG .... Common ground

JA .... Joint activity

SA .... Situation awareness

TTL .... Temporal trace language

1
Introduction

A glance at the past few decades clearly reveals the rise in the global aviation industry. Air transport is now an important and efficient way to travel for many people. This mode of transportation provides immense advantages when travelling large distances, particularly intercontinental. Not only has air travel brought people closer together globally but it has opened a realm of opportunities for countless people. The aviation industry and air traffic management exhibit an innate complexity due to the large number of agents (human and machine) and their interwoven interactions. For such an extensive global network to work, the sociotechnical systems should be well-organized and should also have the ability to cope if and when the operating conditions deviate from nominal conditions. Hence, these systems must be well-coordinated and robust. Additionally, for a complex sociotechnical system like air transportation, it would be prudent to have anticipatory and adaptable capabilities. This would mean to not only predict and plan around a potential threat but even learn from it for future reference. Therefore, such systems are also preferred to have resilient properties.

Air traffic management (ATM) safety practices formed over the years are in accordance with the traditional safety perspective, known as **Safety-I**. Safety-I works towards an approach where the number or adverse outcomes are as less as possible or below the acceptable risk limit [11]. This is achieved by either predicting everything that can possibly go wrong during the operations and eliminating the causal factors or by finding the cause after the effect (failure) has occurred and ensuring it doesn't reoccur. Hence, Safety-I is mainly a ***reactive approach*** focused on ***failure avoidance***. The shortcoming of this view is that it concentrates on the extremely small percentage of events that are considered as 'failures' but ignores the extremely large number of events that happen 'successfully' day-to-day, as can be seen from Figure 1.1. Is such an understanding of sociotechnical systems enough to ensure their safety?

As sociotechnical systems continue to get more complex, the need for an updated view of safety has emerged. We now understand that focusing only on the lack of safety is not enough to ensure safe operations but we also need to understand how things usually go well. This modern view of safety is known as **Safety-II**. Understanding how things usually go correctly will help us ensure that

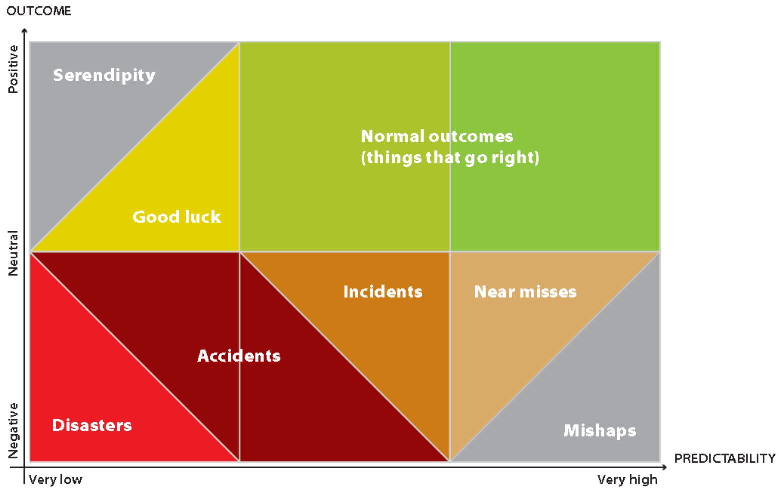

Figure 1.1: The possible set of outcomes

they always do (as much as possible), in turn reducing the things that go wrong. Moreover, *Safety-II focuses on a sociotechnical system's ability to succeed under varying conditions, so that the number of intended and acceptable outcomes (in other words, everyday activities) is as high as possible* [11]. This means that the things that go right or wrong emerge from the same set of actions occurring under different conditions/environments. This approach is ***pro-active*** and focuses on ***enabling success***.

In ATM, like many other sociotechnical systems, processes and interactions take place between numerous agents. These agents can be human or non-human (technological) and additionally, interactions take place not only between human-human or machine-machine agents but also as human-machine interactions. Such systems must be approached as complex **sociotechnical systems (STS)**. The study of STS not only involves technical systems but also operational processes and the people who interact with technical systems. Sociotechnical systems are mostly governed by organizational policies, procedures or protocol. More importantly, STS exist because multiple agents come to work together with the aim of achieving certain goals. This is because of numerous interdependencies and intentions. Such sociotechnical systems require (or exhibit) many coordination processes which can, to a certain degree, ensure the achievement of these goals. While standardization of a complex system can enable better coordination between agents and enhances predictability between them as well, does this always work in complex systems?

This master thesis aims to try and gain a deeper understanding of the underlying coordination mechanisms in complex sociotechnical systems, like ATM. This is done by analysing the implicit and explicit coordination processes in an ATM case. Chapter 2, focuses on a comprehensive review of the sources used in this master thesis. Chapter 3 presents the academic challenge along with the research objective. Chapter 4 describes the methods used to analyse the coordination along with the ATM case that will be analysed. Chapter 5 presents this analysis and the discussions regarding the meaning of obtained knowledge.

2
Sources from Literature

The study of coordination mechanisms has only been around for a couple of decades. Although coordination theory can easily be linked to any interactions or connections in any system or organization, and even day-to-day life, it presents a lot of challenges in analysing or formalizing. This is mainly due to the limited understanding of how the *human factor* operates. This section goes on to describe some research on complex systems and coordination mechanisms that is currently present. However, the main focus of this chapter is to present the literature that has been selected to be incorporated in this master thesis, after a broad literature review.

2.1. Complex systems

A **system** is set of things working together as part of a mechanism or an interconnecting network. It can also be a set of principles or procedures according to which a system runs. This system might be part of a larger complex whole which comprises of numerous interacting systems working together towards achieving a common goal.

A **complex system** is usually a system featuring a very large number of interacting components (like agents or systems) whose aggregate behaviour is non-linear and hence, cannot be derived from summation of individual component's behaviour. The study of complex systems deals with better understanding the interactions and behaviour of the components. Furthermore, this study also deals with the interaction of the system with its environment. Since, the aggregate behaviour of such systems is non-linear, it is crucial to better understand *indirect effects*. However, this is not a simplistic task because majority of the causal relations are not apparent.

When it comes to systems that include human involvement in any way, from interpreting the output of the machine to a team of rowers, the human-factor is added and the system should be seen as a sociotechnical one. As the human brain and consciousness are only partially understood, sociotechnical systems by definition are also complex systems.

The Figure 2.1 shows a rather exquisite and interesting network of Twitter interactions. This image has been reproduced from a paper published in "nature

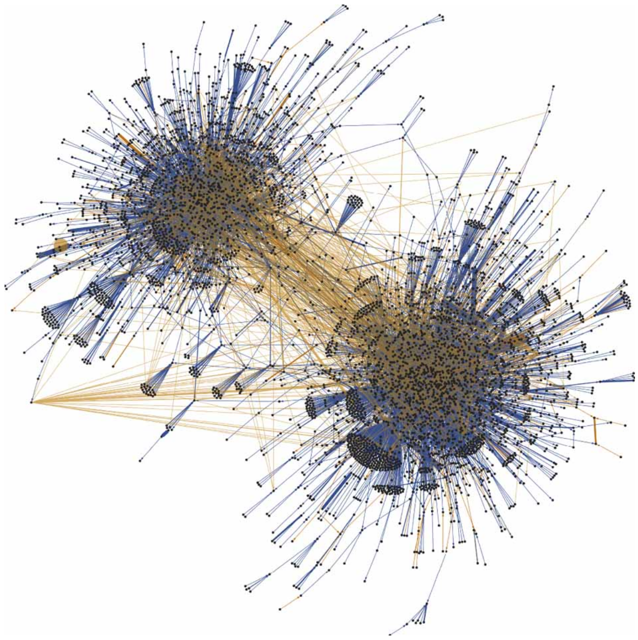

Figure 2.1: Complex network depicting twitter interactions, Reproduced from a paper by Alessandro Vespignani [17]

physics" titled 'modelling dynamical processes in complex sociotechnical systems' authored by Alessandro Vespignani [17]. This image shows the diffusion network for the hashtag "gop". Every node represents an individual Twitter user. Every user can re-tweet posts (blue edges) and/or 'mention' posts (orange edges). This image helps to put in a certain perspective how interconnected, complicated and emergent a complex sociotechnical system is. For a system like ATM, that not only has more complexity in interaction and requires higher precision and accuracy but also has a lot more at stake, the challenges in understanding and formalizing can be quite tricky.

2.2. Coordination

Coordination is a commonly used word and can simply be understood as the act of working together in some organized way. For further specification, the dictionary defines coordination as follows, "*the organization of the different elements of a complex body or activity so as to enable them to work together effectively*". From the paper on Coordination Theory by Malone et al. [13], the narrow definition of coordination is given as follows:

"**The act of managing interdependencies between activities performed to achieve a common goal**" [13].

While all these definition are accurate, a number of definitions exist, each depending on its respective context. Moreover, coordination can be a result: '**state of coordination**' or it can be a process: '**coordinating**'. The theory on coordination has been around for a while and is predominantly seen in the fields of CSCW (Computer Supported Collaborative Work) or ICT (Information & communication technologies) system design/analysis. The last decade has seen a growing interest in understanding the aviation systems from the perspective of coordination mechanisms. As the aviation industry continues to grow, the airspace is getting busier and the complexity of the systems is also increasing. Therefore, these complex sociotechnical systems need an updated understanding.

Any attempt to gain a deeper understanding must start with properly comprehending the very fundamentals of the concept of **coordination**. To this end, the following table presents the various components of coordination and what are the processes of coordination that can be associated with these components. This is obtained from the paper on Coordination Theory by Malone et al. [13].

Components of coordination	**Associated coordination processes**
Goals	Identifying goals
Activities	Mapping goals to activities
Actors	Assigning activities to actors
Interdependencies	Managing interdependencies

Table 2.1: Components of coordination

Table 2.1 shows that coordination has four components; goals which can be achieved by performing certain activities by designated actors which are interdependent between each other. Further, it is noted that the goals have to be identified, structured into activities which should be assigned to actors and interdependencies must be managed. Next, the coordination processes themselves can be subjected to basic categorization as there are more than one basic differences in the way a process or system can be coordinated. Depending on the kind of operations, the complexity and the magnitude etc., the type of process might differ. Usually, more than one coordination mechanism is implicitly or explicitly used in real-world interactions. Henry Mintzberg identified three basic coordination mechanisms (Figure 2.2) in 1979; coordination by mutual adjustment, coordination by direct supervision and coordination by standardization [14].

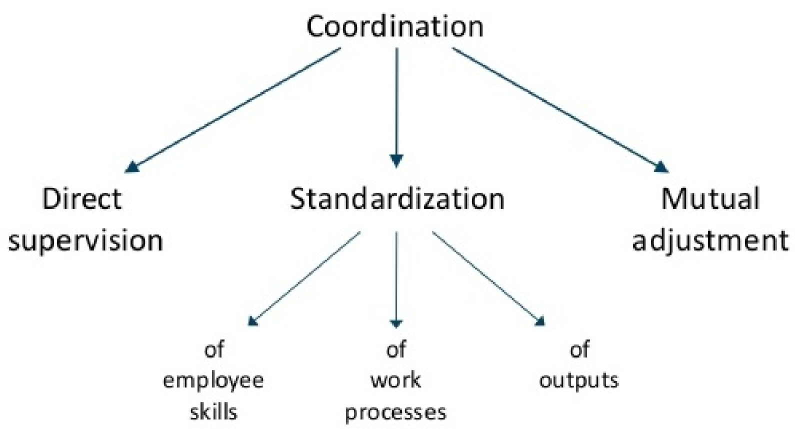

Figure 2.2: Henry Mintzberg's 5 coordination mechanisms

Mutual adjustment is the simple process of informal communication, used either in very small companies or in extremely complicated systems (in collaboration with other mechanisms). Mutual adjustment is mainly useful when the future uncertainties are quite high. **Direct supervision** is when one person takes responsibility for others' work to achieve coordination, by instructing and monitoring others. Levels of hierarchy increase as the the system complexity increases. Using **standardization** to achieve coordination can be done in three ways;

1. Standardization of work processes - the same steps in the work flow should be followed always.
2. Standardization of outputs - the same output should be received regardless of the steps taken.
3. Standardization of worker skills - the skill set of each worker is identical so there is high interpredictability among workers.

Henry Mintzberg's five coordination coordination mechanisms provide an essential overview of how teams enable coordination and also how the system achieves a state of coordinating. However, this view does not explain how the coordination mechanisms themselves work and what part is played by human cognition. In any organization where human-human or human-machine interaction exists, the importance of the human factor must be recognized. High-risk organizations highly standardize their operating procedures in order reduce the 'human risk factor' by streamlining human actions [10]. The rules and procedures are developed over time by observing failures and making safeguards. While this makes sense, it might not be enough for all types of complex systems. Almost 4 decades later, we now have a better perspective on coordination mechanisms.

2.3. Coordination in complex systems

In case of large organizations or a system involving multiple agents (human and/or machine), team coordination requires some underlying coordination mechanisms or processes that enable coordination over time. These processes and mechanisms are mainly of two types, **implicit coordination** and **explicit coordination**. The paper, 'Explicit vs. Implicit Coordination Mechanisms and Task Dependencies: One size does not fit all' by Espinosa et al. [7] elaborately presents this theory.

Explicit coordination

Explicit coordination encompasses the mechanisms used to organize tasks like procedures or protocols. It refers to a more administrative and less personal way of doing tasks. Explicit coordination also includeds oral, visual, personal communication. This kind of a way of managing team coordination processes tends to be well regulated and the interdependencies are highly predictable. This way of coordinating has been well studied and understood in the past years. Being explicit in nature, the observation, study and implementation of such methods is very convenient. Explicit coordination is well suited for many large organizations and teams. However, it is also not an optimal way of management in many other kinds of settings. For example, in a high-risk complex system, like an operating theatre, not every move can be already predicted and hence not every 'task' can be pre-set. There exist many settings where a strict protocol may not be the best way to proceed and flexibility might be very important.

Implicit coordination

In the recent past, the attempts to better understand human cognition have risen. What goes on "inside" the human mind is much more challenging to understand as compared to what humans actually do (explicitly). When it comes to a machine, the implicitness is understandable since we design it. But even today, we do not completely understand the human mind. Moreover, being implicit in nature, it is not easy to observe or study such coordination processes. When coordinating explicitly, the agents are consciously aware of it. On the other hand, implicit coordination usually occurs without the agents consciously recognizing it's occurrence. This kind of coordination is enabled by team's shared cognition. As we all must have experienced first-hand, a team's shared cognition improves as they continue coordinating over time. Implicit coordination mechanisms are those which help the team to explain and anticipate *task states and member actions* [7]. As mentioned earlier, it's not easy to identify implicit coordination. This also makes it extremely difficult to detect when a certain implicit coordination process is missing or not performed.

Awareness

In any complex sociotechnical system, both implicit and explicit coordination processes are necessary. Presence of protocols or some form of standardization also enables implicit coordination. This is because established procedures make activities predictable between agents which can enable the team members to be pre-prepared for anticipated actions. Explicit coordination can also be very crucial in many high-risk situations, like in an operating theatre. Every action by every surgeon is explicitly stated so that everybody in the operation room have the same *awareness* regarding the action taken. The team's situation awareness (SA), similar shared knowledge, transactive memory (knowing what the others know), being aware of what is going on and who is around enables coordination. While explicit coordination mechanisms are able to generate or update a certain awareness, implicit mechanisms are required to recognize the need to update the SA itself. Therefore, both implicit and explicit coordination mechanisms can play a vital role in shaping the SA of an agent. When it comes to awareness, there are many layers and is often studied in the Theory of Mind [9]. An agent may/may not be aware about something, an agent may/may not be aware of what they are aware of, an agent may/may not be aware of what another agent is aware of, an agent may/may not be aware of what the other agent knows of him/her. This leads to the inference that higher the situation awareness, better the coordination.

The study and analysis of coordination mechanisms has been around for a few decades but only within a limited scope. These studies are predominantly seen in the software and ICT world. As the study of explicit coordination is relatively simpler, it is no surprise that it has overshadowed the study of implicit coordination and human cognition. More recently, in the medical field, these studies have been given an importance. This is because medical and surgical science is a very complex high-risk system. The past few years of research work also show the progression of coordination research in the field of ATM safety. The updated views of safety (Safety II) are very important to futuristic safety programs (like SESAR or NextGen) because these programs focus on proactive safety practices. This means that instead of trying to regulate the mistake out of the system, the system learns to cope with the mistakes and be resilient. This also means that the system focuses to enable successful actions instead to disabling unsuccessful actions.

However, it is also important to address **why** it is challenging to study implicit coordination or human cognition. This is mainly because of the level of uncertainty involved. In coordination by standardization, it is fairly clear what the next step will/should be. It is also clear why because the protocols and procedures dictating these actions already take into account the 'why', the 'what', the 'how' etc. In case of implicit coordination, there can never be a cent percent surety of what the next action could be. This is simply because the human mind cannot be wholly predefined. The sheer magnitude of factors that affect human cognition at every point in time are quite impractical to define. When compared to the problem of optimization, which requires to optimize some goal when subjected to certain boundary conditions, the study of cognition works in the opposite way. By understanding the most basic *connections* or *causes*, the rest of the system emerges on its own. There is no optimizing and no boundary conditions. Why is optimization not the best way to go in this case? This is because what might seem to be optimised in a high-risk complex system might just be extremely unsafe, nestling many undetectable or unforeseeable disasters.

2.3.1. Joint Activity

To understand coordination in complex systems, it is prudent to start with the simplest of questions; **why** must the agents coordinate and **can** the agents coordinate? As mentioned in section 2.2, coordination is the management of dependencies between tasks to achieve a common goal. If there do not exist any interdependencies, there won't be anything to coordinate. Hence, having to be dependent on other agents in the team is essentially a criteria for coordination to take place. In the study, "Common Ground and Coordination in Joint Activity" by Klein et al. [12], the concept of **Joint Activity** has been closely described. It is stated that the concepts of joint activity (JA) and team coordination are related quite closely. When attempting to understand coordination processes, the concept of JA takes quite an abstract view on coordination activities. This concept also takes care of the two simple questions posed previously. Once we know the 'why' and the 'can', then there exist many ways to choreograph the joint activity. When the participants enter a joint activity, they are required to coordinate because at least some (if not most) of their tasks affect other's common goal-oriented tasks [12]. Although, to properly grasp human cognition, one needs to dive down to the extreme specifics of these abstract concepts and the concept of JA is a jump up. However, it is believed to be that obtain a rich analysis and understanding, one must start from the very abstract and then approach the specifics.

The following Figure 2.3 has been reproduced from the work of Klein et al. [12] and clearly focuses on the three main details of JA. To enter a JA, the participants must satisfy the criteria. Once the criteria is sufficient, the participants must also meet the requirements to engage in the JA. Subsequently, the JA has to be choreographed and this defines how the JA is actually undertaken.

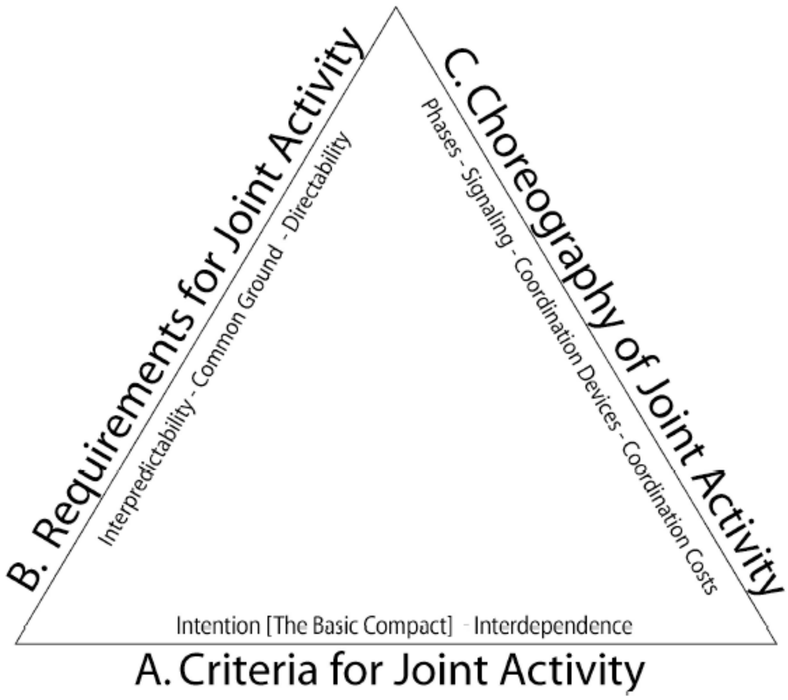

Figure 2.3: The Joint Activity triangle. Reproduced from Klein et al. [12]

Criteria for Joint Activity

There are two criteria that should be satisfied to engage in a JA. The first is the **intention** to work together (to achieve a common goal). The second is the existence of some **interdependencies** among the participants. As mentioned earlier, this is essential because there wouldn't be anything to coordinate without interdependencies. Therefore, the participants must want/intend to work with the other agents involved, to achieve a common goal, in addition to the fact that they need to.

Requirement for Joint Activity

There are three requirements that need to be met for a JA to occur. If one or more of these requirements are not met, the JA can still occur but not efficiently. Coordination breakdowns might also occur frequently affecting the teams' overall performance. The first requirement is **interpredictability**. This means that the team's actions and and processes are predictable within the team and each team member makes their actions predictable for the others. Secondly, the team should have **common ground**. *Common ground (CG) refers to the common knowledge, common beliefs or common assumptions between team members.* CG enables interpredictability as well. When it comes to CG, the participants of JA can perform many activities to support it [12]:

1. Sustaining CG by reminders or clarifications.
2. Updating others about any changes in states.
3. Monitoring others to see if CG is being compromised
4. Detecting anomalies - potential loss of CG.
5. Repairing lost CG.

The third requirement is **directability**. This refers to the ability to direct others explicitly wherever needed, like a new direction or a solution etc. This requirement enables better management and control.

Choreography of Joint Activity

A JA is undertaken in **phases** as it is certain phases of activities that need to be coordinated. The participants of the JA work towards coordinating phases to achieve the common goal. Also, all participants must inform other participants when they wish to leave the JA or they have succeeded with the completion of their task. The participating agents might or might not have the ability to *directly signal* (visually, aurally etc.) one another. This ability is called **signalling**. The opportunities that the agents have to signal each other (to directly interact) will also determine how to the JA progresses. The same holds for the **coordination devices** used by the participants. In most of the cases, the tasks and activities are coordinated according to a prior agreement or pre-established convention etc. Depending on what kind of coordination device is used, it helps to understand another layer of coordination mechanisms. Finally, the **coordination costs** are liabilities and all the overhead of coordination that is (time, effort or resources) faced by the participants of JA. The coordination costs have not been studied in this thesis.

2.3.2. Co-ladder model of coordination

When talking about **how** team coordination (within a team or between two teams)is undertaken, the concept needs further elaboration. As already mentioned, highly complex systems usually achieve coordination by high levels of standardization. There usually exist rules and regulations that govern these procedures. It is when some failure occurs that these rules are put into place or when a failure is predicted, the rules act as a safeguard. Standardization works quite effectively until the system becomes too complex. Too many rules and regulations might constrain flexibility when needed most by the agents; non-routine events. Furthermore, too much reliance on standard practices might prove to be detrimental in an abnormal situation that requires a non-routine & creative solution. This has been discussed in "The effects of different forms of coordination in coping with work load: cockpit versus operating theatre" by Grote and Zala-Mezö [10]. In abnormal situations, the team or an agent must respond appropriately and then re-plan according to requirements. Standardization will not always prove to be helpful and hence, some 'local control' to the agents might be more appropriate. This approach is in-line with coping with uncertainties rather than minimizing them.

The co-ladder model of coordination and communication categorizes eight types of information that one agent (or team) can communicate to another [4]. These information types are represented as nodes in the diagram while the links between these nodes show the coordination processes that transform one type of information into another. Also, all the coordination processes take place over a temporal (x-axis) dimension. Figure 2.4 shows the final co-ladder model reproduced from Chow et al. [4].

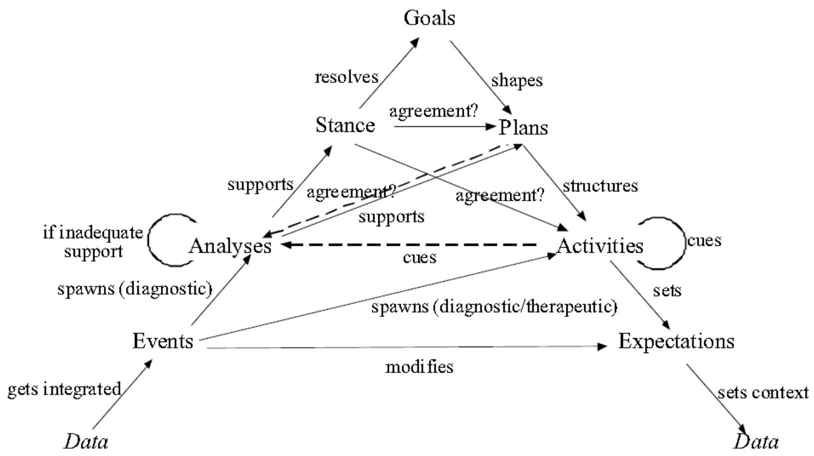

Figure 2.4: Co-ladder model of coordination. Reproduced from the work of Chow et al. [4]

Along the y-axis of this model, the scale ranges from the causal nature of constraints to an intentional nature. This means that the lower-level information (data, events, expectations) is causal in nature and might stem externally. Whereas, the higher-level information (goals, plans, stances) is more intentional in nature and might stem, mostly, internally. For example, the goals and plans are intentional in nature since the agents form these higher-order goals and plans for specific reasons. On the other hand, raw data is usually obtained from external observations. The basic form of the co-ladder model and the simple transitions between processes have been described below. Subsequently, Chapter 4.3.2 elaborates in detail these interactions and how they were used for analysis.

Data

The raw data or the base data values are the most elemental type of information available to the agents. This information can directly be observed from the external environment (extreme thunder and wind could indicate something) but also be provided more explicitly (instruments providing critical data like flight level or airspeed). However, this raw data is meaningless unless it is processed and some meaning is derived from it. This data is available to the agents and they can choose to or not to act on it, process it, communicate it to other agents etc.

Events

When the base data values are processed and understood as some meaningful information (usually with a context but not expected), it forms an event. Usually, data gets integrated into an event over a period of time. In essence, the data and an event is the same thing but with different levels of perception. For example, seeing that the battery sign is red and blinking is raw data but understanding that the battery is about to run out is an event.

Analysis

An event can often spawn analyses, specially if it is not an expected or known event. The analysis node encompasses the agents observation and interpretation, the agent's understanding and evaluation. Since this a personalized process, it can lead to different interpretations and understanding of the same event, by different agents or teams. Therefore, in complex systems, many parallel analysis are performed by different participants and this helps in evaluating the event from many perspectives. An analysis leading to unsatisfactory conclusions or interpretations can cue further analysis. This goes on until the team has some kind of a common understanding of the event.

Stance

The final interpretation or conclusion that is arrived at after performing analyses is known as stance. Stance is a combination of a position towards a significant issue along with the explanation for that position [4]. Therefore, stance can be a major decision or even a complete change of a goal. A change of stance is usually because of a major shift in the agent's understanding, usually because of new information that becomes available. Hence, stance is also quite intentional in nature. The stance can evolve goals, plans and also trigger activities.

Goals

Goals are at the highest level in the co-ladder model. Along with being quite intentional in nature, goals are higher-order and general in nature. Agents engage in a coordinated JA to work together to achieve a common goal. Chow et al. describe goals as states to be achieved by certain agents at a particular time [4]. In a complex sociotechnical system, many different goals might be active simultaneously. These may or may not be in conflict and some might have less importance than others in different moments in time. Furthermore, at any given point in time in a complex system, different teams (or agents) struggle with different goals and progress by making essential trade-offs. To make this work, the team members make their goals known to others which enables coordination in a team.

Plans

To achieve a goal, many tasks or activities are needed to be performed by individual agents or teams. The structuring of these activities (in terms of when to perform what activity and by whom) is usually how a plan is formed. The higher-order goals help in shaping plans. However, as one can imagine, a plan cannot be formed without checking feasibility aspects. So, formation of plans also requires analyses, which not only helps forming plans but also evolving or altering plans as time progresses.

Activities

Activities are inclusive of all the tasks, actions or a series of them that are performed by the agents. The nature or these activities can be physical or virtual (software based). These activities are performed in accordance with the plan but that is not the only way activities can happen. A major change in stance or the occurrence of certain events can also trigger some activities (in a diagnostic or a therapeutic scope). On the other hand, activities themselves can cue other activities and can also cue analyses.

Expectations

When activities or tasks are performed, certain expectations are set in terms of what will happen next. These expectations are usually by the agent who performs the activity from some other agent. In addition to this, events also modify expectations. Occurrence of an event can already modify the expectations of the team regarding what data is being collected and what it means. Expectations are usually regarding raw data and when this observed raw data deviates from the expectations, it constitutes an event.

2.3.3. Multi-Agent Situation Awareness

When trying to gain a comprehensive understanding of sociotechnical systems, it can prove quite helpful to try and formalize the coordination processes mathematically. In the ICT domain, multi-agent system modelling and analysis are fairly common. Such an explicit coordination can be formalized because these systems, after all, have been defined by a human-programmer. When it comes to formalising the human in the multi-agent system, it can prove to be difficult. This takes us back to the shortcomings in the understanding of human cognition. Unlike analytical models, formalization of complex multi-agent systems is not to find the perfect solution but to observe system states at any time [15]. This is because we are trying to gain a better understanding of the complex system's dynamics and are not optimizing. Although this field of research continues to grow, there still does not exist any wholesome study of coordination in complex sociotechnical systems which not only shows the conceptual backing behind team coordination but also presents a supporting and well-grounded mathematical model. This model can not only provide a clear view of what's happening but allows us to experiment and see what could have happened or what might.

Agent-based modelling of complex sociotechnical systems revolves around the concept of **multi-agent situation awareness (MASA)** [2]. Broadly speaking, awareness is the state of being conscious of something (other people, the surroundings etc.). Following that, situation awareness is having the knowledge or perception of a particular situation. In 1995, Endsley [6] presented the following definition of situation awareness (SA):

Situation awareness refers to the level of awareness that an individual has of a situation; to an operator's dynamic understanding of 'what is going on'.

The study of coordination has gone up along with the study of human cognition and these developments tell us that the human factor should not be regarded as a risk factor in the system. In fact, the social abilities and relations between agents should be at the core of any system design [2]. The article "Modelling situation awareness relations in a multiagent system" by Blom and Sharpanskykh [2] presents a mathematical modelling framework for the MASA relations. This mathematical model supports all the three different schools of research on SA. By two of the schools, SA is considered to be either a product of gaining awareness or the process of gaining awareness. The third group, however, sees SA as a combination of the product and the process. The third school of research describe SA as a *generative process of knowledge creation and informed action* [2]. Keeping in mind the social beings humans are, this paper points out the insufficiency of the classic individualistic agent models (like the Belief-Desire-Intention model). Since every interaction of a human being with the environment or other agents will be influenced by the human's internal mental models, the social aspects should be considered fundamental and not an overhead.

The framework considers a multi-agent system (MAS) of N agents $A_i, i = 1, ...N$. It is assumed that at time t, A_i may have one or more **state elements**. State elements are the states that an agent can have about itself, about the environment or about other agents (like noticing that it is raining outside or having experience in flying an Airbus A330). It is important to note that even non-human agents (like the aircraft) can have state elements (known as base states, like having the position of liftoff) but these agents will not have any awareness whatsoever. State elements can be denoted by $x_{t,i}$ where x is the state element of agent A_i at time t. Agents may maintain state elements about it's other state elements or of another agent, A_k. These MASA relations between agents are depicted by S_i^k (SA of agent A_i regarding agent A_k). To denote the SA of an agent A_i regarding another agent A_k at time t, we use $\sigma_{t,i}^k$. The $\sigma_{t,i}^k$ relations are mainly used to denote the agents updates of SA. As complex MAS are extremely dynamic in nature, all the state elements and their relations will vary over time. This updating of an agent's SA about itself, other agents or the environment is necessary for the agents to have good SA which will help in working effectively. Finally, agents may also have state elements in the present regarding some future state of themselves or of other agents. There future-oriented state elements are called intents. An intent of an agent can be an expectation of another agent. In this case, the expectation is not only for a future time point but lasts from 'now' till 'then'. Section 4.3.3 presents some general equation examples used for this formalization.

2.4. Common Ground in coordination

Common Ground is extremely essential for any kind of joint activity involving a team and multiple agents interacting within this team. It has been stated that common ground is what makes coordination and joint activity work [12]. The term, common ground, has been around for quite a long time and is now well incorporated in modern social psychology. According to Clark and Brennan [5], **common ground refers to the collection of mutual beliefs, mutual knowledge and mutual assumptions**. Klein et al. categorize common ground into the three following basic categories [12]:

1. ***Initial common ground*** - This CG refers to all the relevant knowledge and history the agents bring with them when engaging into a JA. Along with the shared knowledge of the world, this also includes all the common knowledge the participants might have regarding the joint task they are engaging in.
2. ***Public events so far*** - As can be inferred from the name, this encapsulates all the knowledge regarding the events so far. The activities (expected and/or unexpected) that occur in a joint activity can constitute events and the common knowledge of this history is important, to enhance anticipatory processes.
3. ***The current state of the activity*** - The knowledge of what is the actual physical state of any process constitutes CG regarding the activity's current state. Knowing this current state often enables and prepares for the next activity or task in the coordination process.

In its simplest form, common ground refers to a basis of common interest or agreement. As mentioned earlier, common ground is the common knowledge that the participants of a joint activity have. It encapsulates common beliefs, knowledge and assumptions of the agents. Klein et al. have also identified what are the most important CG agents have;

1. The roles and functions of each participant.
2. The routines that the team is capable of executing.
3. The skills and competencies of each participant.
4. The goals of the participants, including their commitment to the success of the JA.
5. The "stance" of each participant (eg. his/her time perception, fatigue level, etc.)

The essential elements of common ground have been listed earlier while explaining the concept of *Joint Activity*. These were mainly processes like sustaining, updating, monitoring or repairing of common ground. Hence, we see that there exist many settings where participants must have unchanging CG (for eg. participants having one same goal during the whole phase of coordinated JA) and they must sustain and monitor this. There are also other settings (most complex systems) where the processes of updating CG along with detecting anomalies and repairing CG are much more used and crucial. Since, complex systems are dynamical, the very nature of these systems require constant updating of common ground. This also implies that common ground can have many faults and breakages at many time-steps between any number of combination of agents. This is true and hence the need for updating, monitoring, repairing CG arises. The aim continues to be to detect this loss of CG before it turns into a serious accident from which recovery is difficult.

During the process of coordinating, especially in complex sociotechnical systems, it is very essential for the agents to be aware of the states regarding which they need to have, maintain or monitor common ground. As common ground enables interpredictability between agents, they must be able to predict other agent's actions or intentions to a certain degree. Agents should also be able to detect loss of CG before this loss becomes irreparable. The agents must also remember to timely update CG regarding certain important (and dynamic) states. The loss or CG (temporary or otherwise) is inevitable simply because the world we operate in is very dynamic and largely unpredictable. In addition to this, all agents perceive everything around them personally. Such fundamental differences tell us that a complex system inclusive of the human factor will continuously have loss of CG. Hence, the need to maintain, monitor and update common ground is very critical and real.

When talking about situation awareness and common ground, there exist multiple levels. First off, if two agents have the same knowledge about a certain state (of themselves or of the environment, for eg.) then both these agents are said to have a common ground regarding that particular state and this is first level of CG or awareness. Next, when an agent knows that the other agent has an awareness about a certain state. This case pertains to the second level of awareness. However, for the third level of awareness, an agent must be aware that the other agent is aware of what the first agent knows. The third level of CG or SA is not very easily recognisable but plays a very important role in sustaining CG. The incorrect assumptions made in the third level and the second level of awareness of common ground usually lead to coordination surprises and breakdowns.

2.5. Coordination breakdowns

When coordination occurs in a complex system, many factors can lead to a breakdown in this coordination over time. When there exists insufficient or incorrect CG between agents, the SA of the agents is also insufficient or unreliable. No matter the amount of attention to detail, the breaks in CG are inevitable [12], specially in a sociotechnical system with high levels of uncertainty. As mentioned earlier in the co-ladder model of coordination, we see that CG needs to be monitored, reestablished, sustained, updated etc. As time passes and situations alter, the CG of the agents will be compromised because not all agents will update similarly. This is simply because because interpretations may vary from person to person. It can happen than two agents have different awareness about one single entity, this does not constitute a breakdown. However, when one agent has certain awareness about an entity and believes that the other agent have the same awareness, this can lead to a breakdown in coordination. *Hence, breakdown doesn't arise from the absence of a shared understanding of a situation. A breakdown arises when an agent makes wrong assumptions about another agent* [12].

The article "The breakdown of coordinated decision making in distributed systems" by Bearman et al. states the following definition of breakdown,

"A breakdown occurs when there is a failure of coordinated decision making that leads to a temporary loss of ability to function effectively." [1]

This study only surveyed the coordination and breakdowns between air traffic controllers. However, the breakdowns in coordination between controllers and the aircraft crews or only within the aircraft crews can also be understood using the same concept. This is because when it comes to a human agent in any setting, the aspects of coordination or breakdown will stay the same. In this article, the following causes of breakdowns have been identified [1]. Some examples of these causes have been listed from the study and some have been added for the purpose of this research.

1. **Language**
    (a) Using non-standard terminology and incorrect format.
    (b) Saying something and meaning something else.
    (c) Misunderstanding the intent of others.
2. **Lack of information**
    (a) Neglecting to pass all or enough information.
    (b) Forming a stance or a perception without gathering enough information.
3. **Attention**
    (a) Perceiving information without really understanding it.
    (b) Not paying attention to something crucial because the agent's attention is somewhere else.
4. **Individual differences**
    (a) Different comfort levels with non-standard situations.
    (b) Personality (quiet people, personal conflicts etc.).
    (c) Unprofessional behaviour.
    (d) Expectations (taking short-cuts or assuming that another agent will do something).
5. **Environment and Technology**
    (a) Bad weather conditions.
    (b) Instrument malfunction.

When looking at coordination from a MASA perspective, the differences and inconsistencies in MASA represent the breakdown or the potential breakdowns in coordination. When the set S_i^k is entirely equal to S_k^i, agents A_i and A_k are said to have a fully shared SA [2]. In a system, an SA inconsistency can occur at some time point and go unnoticed for a while (or for very long) unless it becomes explicit or is detected by one or more agents. Once detected, the inconsistency or the SA difference can be repaired. As the occurrence of these differences is inevitable, it is important to focus on the fact that these need to be realized and resolved for the system's efficiency. Usually, explicit communication can repair and restore common ground. This also becomes more challenging if a geographically or culturally diverse team is coordinating (especially for the first time). As mentioned before, the more a team coordinates, the better it will coordinate as time passes.

Klein et al. have identified the following reasons [12] that contribute to the loss of common ground between agents engaged in a joint activity:

1. Lack of experience in working together.
2. Access to different data.
3. Unclear rationale for assigned tasks.
4. Ignorance of differences in stance among team members.
5. Unexpected lack of communication (and the inability to repair this problem).
6. Failure to monitor communication confirmation.
7. Confusion over who knows what.

These reasons clearly indicate that agents experience loss of common ground when they lack some awareness or knowledge pertaining to other agents (or even the environment) in the coordinating process. As mentioned before, loss of common ground is not what usually leads to a breakdown in coordination. It is when an agent makes an wrong assumption about the CG or SA of another agent, the emergence of a coordination surprise is fairly certain. When enabling coordination through standardization, the actions and roles of other agents are made to be predictable and foreseeable. Hence, when an agent does not have common ground about a certain state (when he really should have) and he fails to detect his loss of CG, the other agents will still assume he has CG and will proceed accordingly. Only when this particular agent will fail to deliver (or do) something that he must, the coordination breakdown is detected and can be repaired (or other actions can be taken to resolve this anomaly) and continue with the coordinating process.

2.6. Resilience

In September 2009, Eurocontrol [8] published "A white paper on Resilience Engineering for ATM". Eurocontrol launched a project in 2007 with the aim to understand better the field of Resilience Engineering and its relevance for the ATM world. This paper describes the **resilience** of the system as follows:

"It is the intrinsic ability of a system to adjust its functioning, prior to, during or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" [8]

Furthermore, this white paper on resilience engineering also goes on to describe some more essential concepts that must be studied and understood to enable resilience. The concept of **performance variability** is defined as follows:

"the ways in which individual and collective performances are adjusted to match current demands and resources, in order to ensure that things go right"[8]

Resilience engineering also works on the principle of **equivalence of successes and failures**. This means that the same actions cause good or bad outcomes. While performance variability states that agent(s) adjust their actions as required to ensure good outcomes, a bad outcome merely shows how the system needs to adapt further to cope with these underspecified complex systems. Next, this paper also talks about the systems' emergent properties or resonance. This paper defined **resonance** as:

"A principle that explains how disproportionate large consequences can arise from seemingly small variations in performance and conditions" [8]

This paper concludes by stating the need for resilience engineering for current & future ATM safety practices. It also says that these new safety practices do not replace the traditional methods but complement them. When we talk about the resilience of a system, we cannot write out the human. Regarding the human role in the system, the paper by Stroeve et al. [16] has presented some interesting findings; the occurrence of disturbances is quite common in ATM and that **humans play a crucial role** in the detection and interpretation of these disturbances and also are important to the coordination of the system. The authors have emphasized on the roles of human controllers as a part of this sociotechnical system for their resilient behaviour. Although these specific papers mentioned in this section do not directly aid in achieving the goal of this master thesis project, it is crucial in understanding the project context and placing the research objective in the industrial and global perspective.

The following chapter (Chapter 3) of this report presents the research objective of this master thesis along with how this research fits in the real world practices. Following that, Chapter 4 presents the methodology that is used for the analysis of coordination and the ATM accident case that will be investigated for this analyses. The results of this analysis are presented in Chapter 5 along with the face value validation of the analyses. This chapter also presents the synthesis of these results and a discussion on what it means. Finally, chapter 6 presents the concluding remarks and a look into the future.

3

Research Objective

The main challenge in understanding the underlying coordination mechanisms in complex sociotechnical systems, like ATM, revolves around the "functioning" of the human factor. Although the view that human involvement in a sociotechnical system adds to the risk of the operations is now not as popular as it once was, it is certainly still around. As everything that has been created, automated or designed surely has a human involvement at some stage, human factors cannot ever be truly eliminated. Keeping this in mind, human and machine must complement each other and work together in a way that produces the best results. To enable this, one must understand how the human and the machine work, independently and together. It is much simpler for us to understand how a machine works because it is designed by a human mind. However, the same does not apply for the human mind itself because not only is every human mind unique but also human brain has only partially been understood. The study of human cognition is a prerequisite to better understanding the human-machine interaction, the human-human interaction and also how the human, in general, operates in a complex sociotechnical system.

This research project is another step towards better understanding how a sociotechnical system coordinates. The numerous coordination mechanisms and processes that govern and enable a team to work together can only be efficient over long-term if the **common ground** (2.4) among the participating agents is well established and repaired in case of a breakdown. Agents can have a well established common ground about certain states and might need to regularly update the common ground regarding another state. Agents may also have different level of common ground, which might vary over time, regarding some states. Hence, the focus of this master thesis is on:

Causes, Identification and Repair of the loss of Common Ground in coordination

Aim

The aim of this research project is to better understand coordination in a complex sociotechnical system by analysing an ATM case. This will be done by better understanding the most important and major aspect of coordination, **Common Ground**. The following are the **research questions** that will be focussed on:

1. How do (human and machines) agents coordinate among each other in a complex sociotechnical setting, like a non-nominal ATM scenario?
2. How a (human) agent coordinates and communicates in terms of making a decision or solving a problem etc.?
3. What mechanisms do agents use to sustain, update and repair common ground regarding various states (base states, state properties of other agents which might be human or non-human)?
4. Which mechanisms might lead to identification and/or the repair of the loss of common ground among agents?
5. Do the identified coordination mechanisms actually work and how?

After the analysis of an ATM case, the aim is to understand what kind of common ground exists regarding what states, how common ground is established, updated, monitored etc., how common ground is lost (while being undetected) and how it is repaired (when the loss is detected) and lastly, what leads to the loss (and breakdown) of common ground at all.

4
Methodology

The new approach towards understanding ATM safety focuses on enabling success over disabling failure. This means that we now work towards understanding everyday successes rather than only rare failures. This approach encourages us to assess “safety” by the measure of frequent successes and not by the occurrence of a rare (and usually unexplained) accident event. Air transportation is well known to be one of the safest way to travel in this age and yet, when we encounter an accident, it is something we could never have predicted or even imagined. Is this the risk factor we accept or is it a lack of the basic understanding of how the system works even when there is no failure or accident?

In this chapter of the report, the steps undertaken during this research and the approach towards this research has been elaborated. While in scientifically mature disciplines research work follows a pre-set path of hypothesis → experimentation and testing → results and analysis → conclusions, research work in relatively young fields can be more adaptive and undefined. This is clearly not to say that the scientific work is based on any less factual data. The study of coordination in sociotechnical systems is a young discipline, the understanding from an aerospace perspective is even younger. Added to this is the partial understanding of the human factor which leads to unconventional research methodologies.

4.1. Step 1: Understanding the state of the art

Towards the very beginning of the research project, the very first step is to understand the field of research and the work that has been done, or not done along with the challenges being faced by the research community. This step reveals the predominance of coordination theory in software systems and a slight dispersion into other high-risk sociotechnical domains like medical environments. Over-viewing the literature pertaining to studies in the aerospace domain, one notices a sheer absence of any rich ATM case study that provides an in-depth understanding of the complex interactions in an ATM (sociotechnical) scenario. While there exist many studies with limited analysis, they do not provide a detailed understanding as they do not consider different levels of abstraction.

Chapter 2 mainly focuses on the three different frameworks that have been selected for the purpose of this research. These frameworks provide three different understandings, on several abstraction levels, of coordination in sociotechnical systems. For a rich analysis, the integration of the three frameworks in a single case study can provide an in-depth understanding of coordination (and common ground) in sociotechnical systems.

4.2. Step 2: Selection of an ATM case

To study coordination in a sociotechnical setting, it is possible to select any random day-to-day operational records (transcripts or tapes) as coordination does take place always. However, to perform an elaborate analysis and gain a comprehensive understanding, the following criteria was kept in mind for the selection of an ATM case:

1. As the aim of the research is to better understand coordination in a sociotechnical system, it is prudent to study a case that better exhibits human interaction and coordination since the underlying processes are the same on any given day. Hence, only non-nominal (accidents) cases are considered.
2. An accident case that involves "human errors" like misinterpretation, miscommunication or use of wrong terminology is thought to be the most appropriate choice for this direction of research.
3. An accident case that also exhibits other human factors like stress, distraction, confusion or forgetfulness are also thought to be interesting aspects of study to be better equipped to overcome them.
4. An accident that cannot be traced back to one failure (mechanical or otherwise) and was a result of a series of events that couldn't have been predicted, can prove to be a rich source for analysis of sociotechnical coordination.

Out of the many accident scenarios available in history for analysis, the following case was selected:

Tenerife airport crash: A series of misunderstanding, misinterpretation, miscommunication and confusion led two Boeing 747s to collide head-on on the runway at Tenerife airport in 1977.

While it is plausible that an alteration of one little detail may save the fatality, it is also completely possible that this little alteration may prove to be fatal on any other normal day. How then can we ever predefine or accurately predict a system? The following section elaborates on the events that took place in the selected ATM case and how the case will be analysed.

4.2.1. Selected ATM accident case: 1977 Tenerife crash

In 1977, on March 27^{th}, two Boeing 747 jumbo jets collided head-on on the only runway (Runway 30) at the Tenerife airport located in the Canary islands. This is the deadliest aviation accident in history, claiming 583 lives out of the total 644 people on board the two aircraft combined. The 61 survivors were all from the Pan American aircraft and nobody survived from the KLM aircraft. While no single occurrence or event can be directly causally related to the final crash, there are many sequence of events that led to that unfortunate moment. The *probable causes* which were established by multiple investigations have been listed below;

1. Fundamental cause - KLM captain took off without takeoff clearance.
2. Sudden reduction of visibility and total loss of visual contact prior to take-off.
3. Malfunction of the radio in the KLM cockpit for 3 seconds (caused due to ATCo and PA-CREW speaking simultaneously) resulting in KLM crew not hearing a crucial instruction.
4. Other causes - Use of non-standard terminology, confusion over taxiways and exits, small airport accommodating many more and larger aircraft than it was efficiently capable to handle.

The probable causes do provide a clear picture of how an hazardous situation must have arisen in this case, a further inspection raises some questions such as; If the KLM captain took off without clearance, why didn't the rest of the crew stop this?, standard practices do not allow takeoffs at all in very low visibility conditions so how did KLM crew assume they were okay to takeoff?, if the KLM crew heard a shrill noise in the KLM radio, why didn't they ask the ATCo to repeat the last few seconds of communication? and so on. Such questions can also be raised regarding the actions that the agents usually do and why they do it but are only asked when a failure occurs. This approach to understanding the human element encourages it to be seen as a risk factor. A better understanding of the human element can also update the way we view the human in a system.

Figure 4.1 shows a simplistic reconstruction of the Tenerife airport and how the aircraft moved around this airport space, to finally collide.

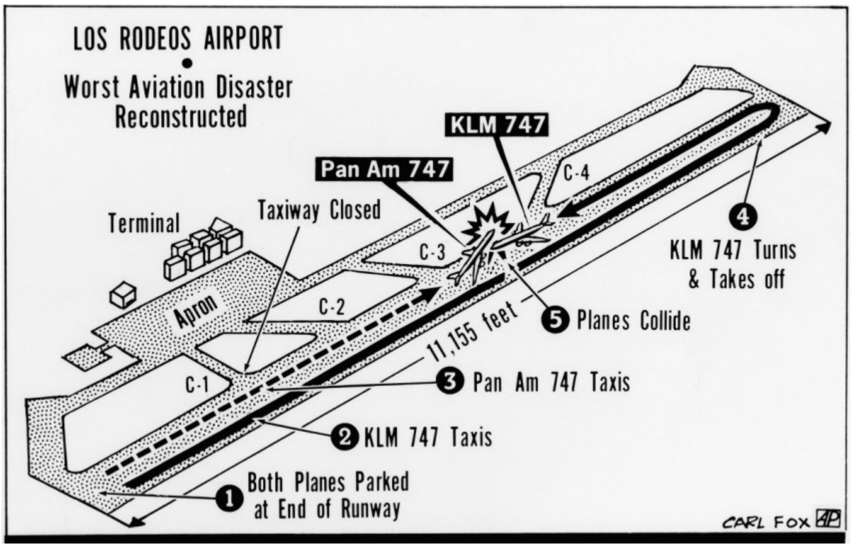

Figure 4.1: Reconstruction of what happened on 27^{th} March, 1977

Following a bomb-blast in the airport terminal of Las Palmas, all the arriving flights to this airport were redirected to other airports which were close-by. The KLM Flight 4805 and the Pan American (PA) Flight 1736 were two of the aircraft which were headed to Las Palmas but eventually redirected to Las Rodeos (Tenerife) airport. The Las Rodeos airport (now called the Tenerife North airport) is quite small with only one runway and hence, mobilising two large 747s could not have been easy (especially considering that there were other smaller aircraft on the airport as well). After waiting at the Tenerife airport for a reasonably long time, the Las Palmas airport was again functional and flights started to takeoff to their original destinations. During this, the KLM staff had not only let its passengers disembark but the KLM captain had also decided to fully refuel the KLM aircraft, mainly to eliminate the need to refuel at Las Palmas. This is because the KLM captain wanted to return to Schiphol Airport before he exceeded his Dutch duty limits. During this time, the PA aircraft was forced to wait behind the KLM aircraft while it refuelled and reseated all its passengers. This prevented the PA crew from taking off before the KLM crew when there was an opportunity to. Due to space restrictions and the position of the two jumbo-jets, the PA crew could only takeoff after the KLM aircraft had taken off.

When the KLM crew completed the process of refuelling and re-embarking its passengers, they were instructed to backtrack down runway 12 to takeoff on runway 30. When an aircraft is to backtrack, it must taxi down the runway in the opposite direction, turn 180 degrees at the runway end and then proceed to takeoff up the runway. Once the KLM crew began taxiing down the runway, the PA crew was also instructed to do the same but exit at the third taxiway (C3 exit). The controller at the approach tower in Tenerife planned to enable KLM to takeoff once the PA aircraft has exited through taxiway C3, following which the PA 747 could also takeoff. Ultimately, however, the KLM crew decided to take-off while the PA aircraft was still on the runway resulting in a head-on collision.

For the purpose of this analysis, the official transcript of the last few minutes before the collision (when the KLM aircraft starts taxiing) will be used. These last few minutes show standard aviation communication between agents but also contains explicit and implicit instances where common ground is found to be lost or incorrect. As this case is already a non-nominal situation (because of the flight diversions), the need for the team to coordinate properly and efficiently is higher. This is because the environment is already out of the realm of *everyday operations*. For the purpose of this case study, the following **agents** have been identified:

1. **KLM-CREW** - The KLM-CREW includes the KLM Captain, the KLM First Officer and the KLM Radio engineer. The flight crew is treated as one agent because they mostly operate as one entity but, in case of the KLM-CREW, the KLM Captain and the rest of the KLM crew have also been separately identified as agents.

2. **PA-CREW** - The Pan American crew includes the PA Captain, the PA First Officer and the PA radio engineer. The flight crew is treated as one agent throughout the analysis as they operate as one entity.

3. **ATCO** - The air traffic controller at the Tenerife tower who was in direct contact with KLM and PA crews is identified as one agent.

4. **KLM-C** - The KLM Captain has been identified as an agent for a specific part of the analysis where he acts seperately from the KLM-CREW.

5. **KLM-RF** - This agent refers to only KLM First Officer and the KLM Radio engineer and has also been identified as an agent for a specific part of the analysis. This is because the KLM-C acts as a seperate agent from KLM-CREW, hence, KLM-RF represents the rest of the KLM-CREW.

6. **TNR** - The Tenerife airport itself has been identified as a **non-agent** (non-human agent) as the crews have a direct interaction with their immediate physical environment and vice-versa.

4.3. Step 3: Applying the frameworks to the case

The three detailed ways to analyse a coordination process were mentioned in Chapter 2. These frameworks have been applied separately over the last few years to understand coordination by investigating different ATM hazards or accident cases. While some frameworks define well, conceptually, what a joint activity is along with why and how it might work (like the work by Klein et al. represented as a Joint Activity triangle [12]), the formalization of coordination still continues to be a major obstacle. The work of Blom and Sharpanskykh [2] is aimed at this very obstacle and focuses on formalizing SA of multiple agents. However, there exists no extensive study that makes use of multiple varied frameworks which encapsulates the abstract understanding along with an specific formalization to investigate a case.

For the purpose of this study, three main frameworks have been chosen. Instead of applying the three frameworks individually and performing an analysis, they are applied together on the selected case. The attempt is to integrate the frameworks together in the way in which they are implemented even though all the three frameworks elucidate and conceptualize the ATM case in their own unique way. In such a way a richer understanding is intended to be achieved by considering coordination and related mechanisms at different levels of abstraction, from different perspectives. The following sections explain how these frameworks have been implemented in analysing the coordination in the last 8 minutes before the crash occurred.

4.3.1. Analysis of coordination between agents

The first step to understand a team's coordination is to start from the basic questions like why does this team need to coordinate? and can this team coordinate?. The Joint Activity triangle (Figure 2.3) [12] can be used to answer these questions methodically. This will provide a basic and a clear perspective on this team coordination. The JA triangle uses three aspects to describe a joint activity. These have been elucidated below:

Criteria for Joint Activity

The two main criteria for a joint activity are that the agents must want and need to coordinate among each other. Hence, this aspect focuses on the agents' **intentions** and also their **interdependencies**. When we see coordination in complex organisations, we know that the agents are working together to achieve a common goal. It is possible that agents might have their own different short-term goals but, as a team, they are working towards the organization's higher-order goals. In this ATM study, a similar situation exists because all the players are performing their jobs and duties but they want and need to be working together to operate successfully, safely and efficiently in the aviation sector.

The agents can have the intention of working together to achieve a higher-order goal and hence be dependent on others to do their part to achieve that goal. However, this kind of a connection is also possible at more local levels since agents might have the need to interact for their short-term goals as well. A good example for this is a dance duet; there is no elegant way a dance duet can go if one of the participants does not want to coordinate at every single step. Taking the same example to explain the need of the two dancers to coordinate, we can see that the need is equally important for them to achieve their goal of a successful performance. Therefore, the agents must intend to work together and should also have interdependencies among them, that raise the need for them to coordinate. Hence, every coordinated activity is different and as the systems get larger, more complex and dynamic, coordination gets increasingly complicated as well as cardinal. In the present study, the criteria of joint activity will be analysed in the start of the activity to see why the agents engage in the joint activity. Subsequently, the entire transcript will also be analysed to see if the agents' intentions or interdependence vary.

Requirements for Joint Activity

Following from why must the agents coordinate, this aspect of the JA triangle checks if the agents can actually coordinate in a meaningful and efficient way. Since the system is complex, sociotechnical and dynamic, the requirements will vary over time (if not at every time-step). Hence, the requirements of joint activity will be analysed at every time-step in the present study. This is checked based on three things which are elucidated below;

1. **Interpredictability** - To work together in a team, the agents must be able to predict each others actions and also, make their own actions predictable. This is usually enabled by standardization, in one form or another (Section 2.3.1). For example, when something is made standard by the use of protocols or procedures, the actions and decisions of an agent become predictable to all other agents. In high-risk settings, like an operation theatre, every participant makes their stance and next action/decision explicitly clear to every other agent so that everybody is on the same page and can be predictable. Hence, it is important to keep in mind that interpredictability is not only what an agent can predict about other agents but also how an agent enables himself to be predictable within that team. In

this study, every time step will be analysed for understanding elements of interpredictability along with what enables it; Common Ground.

2. **Common Ground** - It enables interpredictability between agents and is a very important aspect of coordination. Common ground refers to the common knowledge or beliefs that the agents may have. For example, an agent A is on the runway and knows this and another agent B also knows this about agent A. Hence, both agents A and B have common ground about the position of agent A. As discussed before in Section 2.4, CG is a very complex and multi-layered topic. In a complex sociotechnical system, CG will change very dynamically with the system and the need to update and repair it is continuous. This is because coordination breakdowns usually occur when there is insufficient or wrong CG. When an agent assumes that another agent knows (or will do) something but the other agent does not know this and does not know that he is supposed to either, such a case leads to a coordination breakdown somewhere down the line. Hence, in this study the common ground is analysed at every time step. The focus is to understand how agents maintain and update their common ground, how CG is lost and how the agents detect this loss and finally, how the agents repair the loss of common ground.

3. **Directability** - Directability refers to the agents' ability to be able to direct each other, when required. This is an aspect which is necessary because the agents must be able to change the actions of others if it is required for the accomplishment of the team's goals. Directability is enabled by some form of explicit communication (audio or visual or an order on paper) that directs the other agent towards what they must do. Directability, however, is not the ability of the agents to be able to communicate with each other (that is a part of coordination choreography). In this case study, directability will also be analysed at each time step but it might not necessarily change as time progresses.

Choreography of Joint Activity

After we have covered the *why* and the *if*, the last aspect is to understand how the coordination processes take place. Some defining features of JA choreography have been discussed in Section 2.3.1 which highlight aspects such as phases or coordination, signalling, coordination costs etc. In this study, these aspects of coordination have been identified but are not the central focus.

4.3.2. What goes inside an agent's mind?

Once we gain a perspective on why and how agents interact and coordinate within a team, we proceed towards understanding what happens in every agent's mind when they are coordinating. This part can be tricky because the internal mental processes are extremely implicit and also not easily recognised by the agents themselves. As pointed out, the study of human cognition is extremely challenging and understanding these processes at every time-step, in this study, requires the need to make assumptions as to what thought processes must the agent have

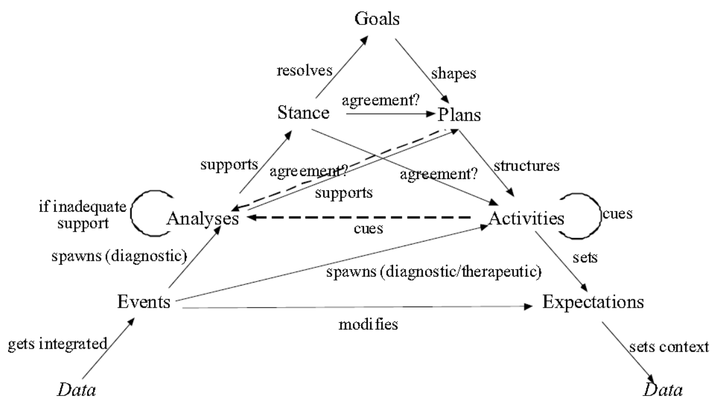

Figure 4.2: The functional model of communication and coordination. Reproduced from the work of Chow et al. [4].

followed to do or say a certain thing. These assumptions are not a major drawback because who better to fill in the gaps of the thought processes of a human than another human?

The preceding figure, Figure 4.2, shows the final functional model of communication and coordination in complex sociotechnical systems developed by Chow et al. [4]. This model also encapsulates aspects of anomaly response and replanning during non-nominal situations. This model helps to semi-formalise human thoughts, how a human would plan, act, analyse or generate expectations etc. For the purpose of this study, this model will be applied to every coordinative/communicative action by all agents at every time-step to see what might be the underlying coordination mechanisms enabling the agent to perform in a team. The following is the description of how this might occur at every time-step for the current case study.

Goals

Goals are usually a higher-order information and remain unchanging for the most part. Team members usually share these higher-order goals (like making profit in a business or operating safely etc.) and perform every other action in-line with these shared goals. However, the goals do not remain unaffected. This is because a major change in context in some situations can lead to the modification or rejection of a certain goal. As seen from Figure 4.2, goals can be resolved by stances and help in shaping plans.

Stance | Plans

A change in stance can change a goal but not only that, the stance must be in agreement with the plan being followed (which is shaped by the goals). Hence, stance can directly affect plans. If the stance disagrees with the plans, the plans are analysed and a diagnosis follows. Also, when a stance changes, it can directly trigger an activity. When an analyses occurs, it must support the current stance and be in-line with the current plans. If this is not the case, the analyses continues and eventually, some aspect will be resolved. Next, plans structure a number of activities that need to be completed in order to fulfil the plan. This also involves the assignment of activities and tasks to particular team members. A number of activities may fall under the same plan until it is accomplished.

Analyses | Activities

An analyses is usually cued when an (unexpected) event occurs and it needs to be made sense of. An analyses can continue until there appears to be some agreement with a plan or a stance or if a goal is resolved. Analyses can also be cued by an activity. When all actions being performed are predefined, other agents' activities will not usually cue an analyses because it is immediately understood and the next step is taken. However, when an activity is not immediately understood by an agent, it is analysed. This analyses usually leads to an update in the plans, more usually than the stance. An activity also generates an expectation by the agent who performs the activity, in terms of what the result (or the following action) might be and by which agent. These activities can be triggered by events, usually in a diagnostic or corrective space. Finally, events can modify the expectations that the agents might have after certain activities have taken place.

Events | Expectations

An integrated set of raw data makes an event. An event can trigger an analyses, an activity or modify an expectation. An event is basically an external and unpredicted occurrence which raises the need for refinement of priorities and actions. On the other hand, expectations are just what the agent foresees to be happening after he has performed a certain action. It is by observing raw data one determines if the expectations were met. If they were not, it constitutes an event and might possibly trigger an analyses.

4.3.3. Multi-Agent Situation Awareness - Formalization

When we have gained an understanding on how the joint activity occurs and what goes on inside an individual agents mind, it can be useful to formalise this information. An agent-based modelling of this coordination can open doors to a specific understanding of coordination mechanisms from an abstract one as it enables analytical analysis and analysis by simulation. Formalising this information will also aid in a deeper understanding of the agents' common ground. Several aspects of CG, like maintenance, updating and loss of common ground etc., can be clearly identified and analysed when modelled. Furthermore, mathematical modelling and simulation also provides the opportunity to validate our understanding of coordination mechanisms, also in variable scenarios. This will not only provide a deeper understanding but also can be used to predict what might be in the future.

The concept of common ground is vital to coordination. Common ground is also closely related to the concept of *multi-agent situation awareness*. While situation awareness can only be an agent's awareness regarding a state of another (aware or non-aware) agent or non-agent, common ground always refers to the common knowledge or awareness that two or more aware agents have regarding a certain state (about one another or a non-aware entity). Hence, common ground can only exist when an agent has an awareness and has a sense of this awareness. Therefore, common ground is an essential concept in a sociotechnical system. To formalise common ground, only the framework provided by Blom and Sharpanskykh [2] can be used. This paper provides a framework to mathematically model situation awareness using agent-based techniques and is the only available framework for the same. The multi-agent situation awareness (MASA) model can be applied to a multi-agent system with N agents, like the present study. This framework requires the identification of state elements for each agent. These states are those regarding which an agent has situation awareness (or SA loss/inconsistency and updates). These state elements have been distinguished as follows;

1. **Continuous valued state elements** - These are the states of the agents that usually provide *quantifiable information* (like speed or altitude) about a dynamic entity.

2. **Discrete valued (mode) state elements** - These are the states of the agents that occur at a time point and do not provide quantifiable information more than the state being *true or false* (like conflict alert [yes/no] or granted takeoff clearance [yes/no]).

3. **Intent valued state elements** - There are states which are intended to be true by the agents at a (or within a) certain *future time* step. An agent's future planned activities, his expectations etc. are a part of intent states.

Once all the state elements have been recognized, the MASA framework [2.3.3] is used to depict the MASA relations between agent i and agent k using S_i^k. S_i^k are used to represent the situation awareness (MASA relations) of agent i about agent k regarding certain state elements. Furthermore, the common ground and its loss or a MASA inconsistency/conflict can also be represented by the MASA relation representation of S_i^k. For example;

- $S_{ATCO}^{KLM-CREW}$ = contact requested

  This relation depicts that ATCo and KLM have common ground about the fact that KLM has requested contact with ATCo. As CG is maintained regarding this state, "contact requested" is enough to show this relation.

- $S_{KLM-CREW}^{TNR}$ = [own position(turn 180), position(turn 180)]

  This relation shows that KLM-CREW has CG regarding it's physical position on the airport. The airport does not have awareness hence KLM-CREW's perception of their own position is compared with their actual physical position on the airport. This relation can also be depicted by only "position(turn 180)" for the sake of simplicity.

- $S^{ATCO}_{PA-CREW}$ = [knows(plan P8)]

  The relation "knows" represents a second level of awareness where the PA-CREW is aware that ATCo knows that PA-CREW is following plan P8. Hence, ATCo and PA-CREW both know that PA-CREW is following plan P8 and CG is maintained. This relation can also be depicted by "knows(plan P8)" for simplicity.

- $S^{KLM-CREW}_{ATCo}$ = [position(standby takeoff), position(taking off)]

  This relation shows incorrect CG or loss of CG. ATCo believes that KLM-CREW has position of standby for takeoff while KLM-CREW was already taking off and thought ATCo knew this.

The SA of an agent i at moment t about a state of agent k is denoted by $\sigma^{k}_{t,i}$, which is updated by agents when needed. An update in SA does not mean that the agents have CG. An update in SA can also lead to loss of CG as it might be a wrong update. When the agents communicate, the interpretation of the message is a function of the two agents, $f^{mi/oi}_{i,k}$(msg). As this information is received, the agents update their SA by reasoning and observations. A lot of CG losses can be attributed to misinterpretation, miscommunication etc. due to audio or visual observations. Examples of updates in SA, through reasoning or other external events, are shown below:

- $[\sigma^{KLM-CREW}_{t10,ATCO}; \sigma^{ATCO}_{t10,KLM-CREW}]$
  $= f^{mi}_{ATCO,KLM-CREW}$(report position(on runway))
  = [position(on runway); expectation(E10, t10+5)]

  This particular set of equations show the SA update of ATCo and KLM-CREW at time $t10$. ATCo has an SA update regarding the position of the KLM-CREW and at the same time KLM-CREW generates an expectation E10 (from ATCo) which lasts for the next 5 seconds. This update occurs as the KLM-CREW communicates with ATCo to report their position update. Here, the superscript *"mi"* refers to the interpretation of the communicated message, which is a function of the two agents involved in this exchange.

- $\sigma^{PA-CREW}_{t15,PA-CREW}$ = plan(P6)
  $f^{r}_{PA-CREW}$(plan(P6))
  $[\sigma^{PA-CREW}_{t15,ATCO}; \sigma^{ATCO}_{t15,PA-CREW}]$
  $= f^{mi}_{ATCO,PA-CREW}$(contact request)
  = [contact requested, expectation(E15, t15+10)]

  This set of equations show the reasoning process of agent PA-CREW from having a plan to doing an action accordingly. The superscript *"r"* refers to the reasoning of agent PA-CREW that led to the contact request. This request further leads to updates among multiple agents as shown previously.

- $[\sigma^{KLM-CREW}_{t50,PA-CREW};\sigma^{PA-CREW}_{t50,KLM-CREW}]$
  $= f^{oi}_{PA-CREW,KLM-CREW}$(visual contact)
  =[position(head-on approach); position(on runway)]

  This set of equations depict the agents' SA update once they have visual contact with each other, approximately 9 seconds before impact. The superscript of *"oi"* refers to the interpretation through observation that leads to the SA update.

Once the first two frameworks have been applied for the analysis of the ATM accident case, the raw data is available for the formalization. Similarly, once the mathematical formulation is completed, it must be able to complement the first two frameworks and be in-line with what was learnt. An appropriate integration and flow is necessary in the implementation of these three frameworks for the fulfilment of the research objective. As several aspects of common ground become explicit, the causes, identification and repair of the loss of common ground will be comprehensible and reportable. The framework provided by Bearman et al. [1] is used to describe and categorize the coordination breakdown, propagated by the loss or common ground, in this study.

4.4. Step 4: Analysis

After applying all the three frameworks, a comprehensive understanding of the ATM case is obtained. A final matrix is created, which can be seen in section 5.4, which showcases the results obtained from applying the frameworks to the selected case. The final matrix must now be analysed to better understand the coordination mechanisms and how they effect common ground in coordination. The following Chapter 5 provides a detailed account of these results and what can be learnt from them. Along with this, the coordination mechanisms are also identified to study the role played by common ground in a joint activity. An elaboration of these mechanisms and their implementation has been presented in section 5.6.

The final step in the analysis is to create mathematical model using TTL language specifications and simulating the model using an agent-based software, known as LEADSTO (A Language and Environment for Analysis of Dynamics by SimulaTiOn). This software has been developed to model the dynamics of multiagent systems both quantitatively and qualitatively. The LEADSTO (or TTL) language uses simple temporal dependencies between state properties of agents and the simulation environment produces temporal traces for a better analysis. The working of this language has been described in detail in section 5.7 along with examples of the specifications used. Once a basic mathematical model is constructed, the LEADSTO software environment can be used to run simulations. This has been in demonstrated section 5.8. Following this, the final step of this research project is to validate the identified coordination mechanisms and how they affect the common ground of agents. Implementation of the identified coordination mechanisms and variability analyses will be done to check for validity. This step of the project can be seen in sections 5.8.1 and 5.9.

5
Results

This chapter presents the results of applying the three frameworks on the accident: the Tenerife crash of 1977. A final matrix has been presented which shows together the results of all the three frameworks. This chapter presents in detail the modelling of coordination with not only the agent-based techniques (ABM) but with a strong theoretical context and explanation. Prior to that, some preliminary information is obtained as each framework is individually used to "model" the accident case. Therefore, the following sections present the preliminary results, the final result matrix (Table 5.6 till Table 5.31) and the assumptions which were made to perform the full study.

5.1. Framework 1: Joint Activity triangle

Many aspects of the JA triangle [12] are identified as generic cases in this ATM accident case. The aspects that vary with time have been addressed in the final matrix. This section presents the abstract understanding that is gained from this analysis.

Intention – Agents have the intention to work together and achieve and maintain common higher goals like safe ground operations, safe air operations, efficient ground operations, efficient air operations, continued job security etc.

Interdependence -

- Dependence of ATCo on aircraft crews: The provision of clearances and instructions by ATCo to an aircraft crew under their supervision depends on the crews' information about the state of their aircraft (position, speed), their intent, requests for clearances and instructions. The workload of ATCo depends on the number of aircraft under his/her supervision.
- Dependence of aircraft crews on ATCo: Ground operations of aircraft crews under supervision of ATCo depend on instructions and clearances of ATCo (for taxi, takeoff, ATC), airport information.
- Dependence of aircraft crews on other aircraft crews on the airfield: Aircraft crews' ground operations are constricted by ground operations of other crews operating on/approaching the airfield at the same time.

Interpredictability - Interpredictability is enabled through;

- ATCo of aircraft crews: shared formal procedures (specifically, request ATCo clearances, execute ATCo instructions), reporting of crews' position and intent, crews' acknowledgement of all ATCo communication
- Aircraft crews of ATCo: shared formal procedures (provide clearances and instructions), ATCo's airport and weather information, acknowledgement of all crews' communication

Directability – Directability is exercised by ATCo in this study by provision of clearances and instructions to the crews by radio contact (explicit communication). KLM Captain provides directives to the rest of the KLM crew on ground operations.

Common Ground – Common ground plays a crucial role and is the main focus of this thesis and has been discussed in detail in Section 5.5.

5.2. Framework 2: Model for communication and coordination

For every step in the official transcript, this framework provides a reasoning behind every action and communication. Incorporating this framework [4] for the current study highlights some aspects of communication and coordination within agents, which are enumerated:

1. For communication involving interpretation and analysis of information, the "Activity (Input msg) – Analysis – Plans – Activity (Output msg)" relational pattern seems to fit best.
   Eg: (ATCo) : P3 $\xrightarrow{A6}$ An2 → P5 → A7
2. For the regular communication requiring no (substantial) analysis, the simple "Activity – cues – Activity" makes most sense; specially for communications that are about acknowledging a previous message.
   Eg: (PA-CREW) : P8 $\xrightarrow{A18}$ A19 & A20
3. Activities always set an expectation for a time in the future, usually involving another agent.
   Eg: (KLM-CREW) : A12 → E12
4. In the beginning, goals shape plans which structure activities and set certain expectations.
   Eg: (KLM-CREW) : G1 & G2 → P1 → A1 → E1
5. However, as time progresses, an activity might cue multiple activities and/or analysis etc. and vice versa.
   Eg: (ATCO) : P5 $\xrightarrow{A24}$ An5 → P9 → A25

In addition to this, numerous goals, plans, activities, expectations, events, analyses and stances of various agents have been identified in the study. The following table shows some of the identified elements and all the identified elements have been listed and described in Appendix A.1. The identified elements are categorized as **G: Goal, P: Plan, A: Activity, E: Expectation, S: Stance, An: Analysis, Ev: Event**. Once all the individual elements have been identified from the selected ATM case, functional model of communication and coordination, Figure 4.2, can be used to discern the flows of interaction between these different elements for each agent. These relations have been represented at every time step in final matrix.

TERM	AGENT	DESCRIPTION
G1	KLM-CREW	Takeoff ASAP
G3	ATCo	Safe and efficient operations
G4	PA-CREW	Takeoff after KLM
P1	KLM-CREW	Backtrack following aviation protocol
P2	ATCo	Guide KLM aircraft following aviation protocol
P6	PA-CREW	Contact ATCo and backtrack (=taxi down the runway) following aviation protocol
A10	KLM-CREW to ATCo	“KLM 4805 is now on the runway”
A40	KLM-CREW	KLM initiates takeoff, release brakes and accelerate
E23	ATCo from KLM-CREW	Expect KLM to report latest position.
E40	KLM-CREW	Expect to takeoff safely
An2	KLM-CREW	KLM-CREW hears ATCo’s plan for them to taxi
S1	KLM-CREW	Realize that PA is still on the runway

Table 5.1: The identified elements

5.3. Framework 3: MASA modelling

The first step in using this framework [2] is to identify the state elements. Many states will be similar to the information elements identified by the previous framework but also additional states that have not been identified there. The following table shows a few of the identified continuous valued state elements. As mentioned earlier, these states are usually dynamic and provide quantifiable information. In the present case study, the position of the two aircraft are the only dynamic states that the crews of the two aircraft exhibit.

KLM-CREW	PA-CREW
position(KLM 747)	position(PA 747)

Table 5.2: Continuous valued state elements

Discrete states, like the name suggests, are those states of agents that take discrete values, e.g., limited set of real numbers and not only 0 or 1. These states may or may not be true at certain time steps and do not provide any further information about the state other than being true or false in that time step. For the present case study, many discrete states can be identified for different agents. However, only the most crucial and varied discrete states of the agents have been demonstrated in Table 5.3. Appendix A.2 shows the detailed table with all of the identified discrete states.

KLM-CREW	PA-CREW	ATCO
goal(G1)	goal(G4)	goal(G3)
plan(P1)	plan(P6)	plan(P2)
plan(P4)		plan(P3)
position(entering runway)	position(entering runway)	
position(on runway)	position(on runway)	
contact requested	contact requested	contact acknowledged
contact established	contact established	contact established
granted taxi clearance	granted taxi clearance	granted taxi clearance (KLM)
requested ATC clearance		granted ATC clearance (KLM)
visual contact (PA)	visual contact (KLM)	
stress due to Dutch duty limits		
impact (PA)	impact (KLM)	

Table 5.3: Discrete valued state elements, table 1

Apart from the three main agents mentioned, other agents like KLM-C, KLM-RF and a non-agent TNR also have discrete state elements. For non-agents like TNR, base states do exist but the agent themselves will never have an awareness about this state, hence it is only a reactive agent. For example, an airport will not have any awareness about it's own visibility conditions (not yet, anyway). The following table 5.4 presents the main discrete states of the several other identified agents.

KLM-C	KLM-RF	TNR
observation(KLM-RF, stop takeoff)	observation(KLM-C, initiate takeoff)	visibility conditions (low)
plan(P13)	plan(P9)	ground radar availability(no)

Table 5.4: Discrete valued state elements, table 2

Finally, all conscious agents must also have intent valued state elements. These are the states that correspond to a time step in the future. These states can be a plan that is to be followed by the agent at a certain time or it can also be an expectation that an agent has from another agent regarding a certain action or task at a particular time in the future. The crews and the air traffic controller have certain future-oriented states, some of which have been presented in the table below (assuming the current time as t).

KLM-CREW	PA-CREW	ATCO
intent(taxi exit C1, t+20)	intent(taxi exit C3, t+40)	
expectation(ATCO, E3, t+5)	expectation(ATCO, E15, t+5)	expectation(KLM-CREW, E25, t+10)

Table 5.5: Intent valued state elements

5.4. Modelling the coordination: Final Matrix

Once all the three frameworks have been implemented and the basic aspects have been recognized and listed out, it is possible to have a chronological analysis of the case study where the application of the three frameworks can be comprehended clearly. The following section shows the final analysis matrix where every time step of the case is viewed through each one of the three frameworks to disentangle the underlying coordination processes. This table presents a modelling of coordination with a rich **theoretical foundation** along with **agent-based modelling** (ABM) techniques. The first column lays out the official transcript for every time step. The second column presents the theoretical understanding of the action at that point in time using the JA triangle [12] which inspects the interaction among agents. The third column presents what's going on inside an agents mind when seen through the co-ladder framework [4]. The last column uses ABM techniques from the MASA framework [2] and formalises each interaction at all time points. Such a matrix is a useful tool to gain an abstract view of the situation along with understanding the specific details at each time point. Additionally, multiple assumptions were made to fill in the gaps since the official records only show what happened (mainly audio communications)and it is not always clear why an agent did something. These are enlisted;

1. All crews and controllers want to follow standard aviation protocols and aim to perform safe and efficient operations.
2. Both the aircraft begin taxiing as soon as the crews receive their respective taxi clearances.
3. The KLM-CREW interprets the provision of ATC clearance as both; an ATC clearance and the provision of takeoff clearance.
4. The KLM-CREW assumes that the PA aircraft is off the runway when they are provided the ATC clearance (as they also do not hear PA-CREW's report of their position being on runway).
5. The KLM Captain initiates takeoff before reporting ready for ATC clearance (as per previous plan) because he wrongly interprets the previous part of the plan, probably because he is stressed.

Communication	Joint Activity	Co-ladder	MASA
t1 = 1658:14.8 (KLM-CREW) – Approach KLM 4805 on the ground in Tenerife. (A1)	KLM establishes communication with TNR ATC to engage in Joint Activity – start coordination phase- **Intention** – to work together to achieve and maintain goals like safe & efficient air/ground operations. **Interdependence** – need to establish first contact required by aviation protocol to start executing operations. **Interpredictability** – initial contact is established between agents through communication and acknowledgement.	**KLM-CREW** G1 & G2 → P1 P1 → A1 A1 → E1	$\sigma^{KLM-CREW}_{t1,KLM-CREW}$ = goal(G1), goal(G2) $f^{r}_{KLM-CREW}$ = goal(G1), goal(G2) $\sigma^{KLM-CREW}_{t1,KLM-CREW}$ = plan(P1) $f^{r}_{KLM-CREW}$ = plan(P1) $[\sigma^{KLM-CREW}_{t1,ATCO};\sigma^{ATCO}_{t1,KLM-CREW}]$ = $f^{mi}_{ATCO,KLM-CREW}$(contact request) =[contact requested ; expectation(E1, t1+10)]
t2 = 1658:21.5 (ATCo) – KLM -ah- 4805, roger. (A2)	**CG** –All the agents are required to follow aviation protocol and all of them know that the others would do so. The agents should be aware that the contact is established. ATCo is also aware of KLM's goal to takeoff ASAP because of extensive delay. **Directability** – instructions through direct radio communications. Coordination device – '**convention**' – following standardized aviation protocols for taxi, takeoff etc.	**ATCo** G3 → P2 P2 $\xrightarrow{A1}$ A2 A2 → E2	$\sigma^{ATCO}_{t2,ATCO}$ = goal(G3) f^{r}_{ATCO} = (goal(G3), observed(KLM aircraft)) $\sigma^{ATCO}_{t2,ATCO}$ = plan(P2) $\sigma^{KLM-CREW}_{t2,ATCO}$ = goal(G1),goal(G2) f^{r}_{ATCO} = (plan(P2), contact requested) $[\sigma^{ATCO}_{t2,KLM-CREW};\sigma^{KLM-CREW}_{t2,ATCO}]$ = $f^{mi}_{KLM-CREW,ATCO}$(contact ack) =[contact established ; contact established, expectation(E2, t2+5)]

Table 5.6: Final matrix, page 1

Communication	Joint Activity	Co-ladder	MASA
t3 = 1658:25.7 (KLM-CREW) – We require backtrack on 12 for takeoff runway 30. (A3)	**Interdependence** – crew needs to obtain taxi clearance and instructions and ATCo needs to know KLM-crew's plan. **Interpredictability** – KLM sharing plans and intents. Expect acknowledgement and taxi instructions according aviation protocol. **CG** – ATCo now knows KLM's plans.	**KLM-CREW** P1 $\xrightarrow{A2}$ A3 A3 → E3	$f^r_{KLM-CREW}$ = (plan(P1), contact established) $[\sigma^{KLM-CREW}_{t3,ATCO};\sigma^{ATCO}_{t3,KLM-CREW}]$ $= f^{mi}_{ATCO,KLM-CREW}$(request taxi clearance, plan(P1)) = [requested taxi clearance, plan(p1) ; expectation(E3, t3+5)]
t4 = 1658:30.4 (ATCo) – Okay, 4805… taxi… to holding, position runway 30. Taxi onto the runway and -ah- leave runway (third) to, your left. (A4)	**Interdependence** – ATCo provides instructions and clearance as requested by KLM, according to their plan. KLM needs the ATCo to provide specific instructions to taxi. **Interpredictability** – ATCo expects acknowledgement for taxi instructions from KLM. ATCo shares plans for KLM and expects KLM to follow. **CG** – ATCo forms a plan in-line with KLM's plan and communicates it to them. KLM now knows that they are cleared to taxi and have obtained exact taxi instructions.	**ATCo** P2 $\xrightarrow{A3}$ An1 An1 → P3 P3 → A4 A4 → E4	f^r_{ATCO}(plan(P2), plan(P1), requested taxi clearance) $\sigma^{ATCO}_{t4,ATCO}$ = plan(P3) f^r_{ATCO} = plan(P3) $[\sigma^{ATCO}_{t4,KLM-CREW};\sigma^{KLM-CREW}_{t4,ATCO}]$ $= f^{mi}_{KLM-CREW,ATCO}$(provide taxi clearance) =[granted taxi clearance ; expectation(E4, t4+5)] & $[\sigma^{ATCO}_{t4,KLM-CREW}] = f_{KLM-CREW,ATCO}$(plan(P3)) = [plan(P4)]

Table 5.7: Final matrix, page 2

Communication	Joint Activity	Co-ladder	MASA
t5 = Begin taxing down the runway (KLM-CREW) (A5) t6 = 1658:47.4 (KLM-CREW) – Roger, sir (entering) the runway at this time and the first (taxiway) we, we go off the runway again for the beginning of runway 30. (A6)	**Interdependence** – ATCo depends on KLM to repeat and follow the taxi instr- -uctions. KLM reports aircraft state of entering the runway to ATCo as ATCo depends on KLM to report their updated position timely. **Interpredictabilit**y – KLM is acknowledg- -ing taxi instructions so that ATCo knows that the suggested plan will be followed. **CG** – KLM reports their change in state (started taxi) and acknowledge ATCo's plan for them. ATCo knows KLM is now entering runway and is planning to exit at C1 instead of C3..	**KLM-CREW** P1 $\xrightarrow{A4}$ An2 An2 → P4 P4 → A5 & A6 A6 → E6	$f^{r}_{KLM-CREW}$(plan(P1), contact established) $[\sigma^{KLM-CREW}_{t3,ATCO};\sigma^{ATCO}_{t3,KLM-CREW}]$ = $f^{mi}_{ATCO,KLM-CREW}$(request taxi clearance, plan(P1)) = [requested taxi clearance, plan(p1) ; expectation(E3, t3+5)]
t7 = 1658:55.3 (ATCo) – Okay, KLM 80 -ah- correction, 4805, taxi straight ahead -ah- for the runway and -ah- make -ah- backtrack. (A7)	**Interdependence** – ATCo provides KLM with the new instructions to achieve the same previous goal – KLM takeoff ASAP. **Interpredictability** – ATCo expects acknowledgement for taxi instructions from KLM. **Directability** – sharing new instructions on radio.	**ATCo** P3 $\xrightarrow{A6}$ An3 An3 → P5 P5 → A7 A7 → E7	f^{r}_{ATCO} (plan(P3), plan(P4)) $\sigma^{ATCO}_{t7,ATCO}$ = plan(P5), not(plan(P3)) f^{r}_{ATCO}(plan(P5)) $[\sigma^{ATCO}_{t7,KLM-CREW};\sigma^{KLM-CREW}_{t7,ATCO}]$ = $f^{mi}_{KLM-CREW,ATCO}$(plan(P5)) =[knows(KLM-CREW, position (entering runway)) ; expectation(E7, t7+5)]

Table 5.8: Final matrix, page 3

Communication	Joint Activity	Co-ladder	MASA
t8 = 1659:04.5 (KLM-CREW) – Roger, make a backtrack. (A8)	**Interdependence** – ATCo provides KLM with the new instructions to achieve the same previous goal – KLM takeoff ASAP. **Interpredictability** – KLM acknowledges the communication. **CG** – KLM and ATCo both believe they have communicated correctly regarding taxi instructions. They believe they have CG. **Coordination breakdown** – Undetected- It is a breakdown because of language – misunderstanding the intent of others – KLM still intends to exit at C1.	**KLM-CREW** P4 $\underrightarrow{A7}$ A8	$f^{r}_{KLM-CREW}$(plan(P4)) $\sigma^{KLM-CREW}_{t8,ATCO}$ $= f^{mi}_{ATCO,KLM-CREW}$(ack new taxi instructions) = plan(P5)

Table 5.9: Final matrix, page 4

Communication	Joint Activity	Co-ladder	MASA
t9 = KLM observes that it has position of being on the runway. (A9) t10 = 1659:10.0 (KLM-CREW) – KLM 4805 is now on the runway. (A10)	**Interdependence** – For ATCo supervision, KLM must report new/changed position of aircraft. ATCo is dependent on KLM to report their position especially because of bad visibility conditions and no ground radar. **Interpredictability** – KLM's position information allows ATCo to better control the execution of the previously defined plan, also in relation to plans for other aircraft. KLM is enabling interpredictability. KLM expecting acknowledgement of position communication from ATCo. **CG** – updating CG by reporting new position or change in state. ATCo has CG for KLM's position. PA-CREW also has CG regarding position of KLM aircraft. Coordination device – **signalling** - explicit direct declaration of new observation from one agent to another through direct radio.	**KLM-CREW** P4 $\underrightarrow{A5}$ A9 P4 $\underrightarrow{A9}$ A10 A10 → E10	$\sigma^{KLM-CREW}_{t9,KLM-CREW}$ $= f^{oi}_{KLM-CREW,TNR}$(position(on runway)) $f^{r}_{KLM-CREW}$(plan(P4), position(on runway)) $[\sigma^{KLM-CREW}_{t10,ATCO};\sigma^{ATCO}_{t10,KLM-CREW}]$ $= f^{mi}_{ATCO,KLM-CREW}$(report position (on runway)) = [position(on runway) ; expectation(E10, t10+5) Also, $\sigma^{KLM-CREW}_{t10,PA-CREW}$ = position(on runway)

Table 5.10: Final matrix, page 5

Communication	Joint Activity	Co-ladder	MASA
t11 = 1659:15.9 (ATCo) – 4805, Roger. (A11)	**CG** – KLM crew is aware that ATCo is aware about KLM crew's position on the runway.	**ATCo** P5 $\underrightarrow{A10}$ A11	f^{r}_{ATCO} (plan(P5), position(on runway)) $\sigma^{ATCO}_{t11,KLM-CREW}$ $= f^{mi}_{KLM-CREW,ATCO}$(ack position report) =knows(KLM-CREW, position(on runway))
t12 = 1659:28.4 (KLM-CREW) – Approach, you want us to turn left at Charlie 1, taxiway Charlie 1? (A12)	**Interdependence** – KLM-CREW is dependent on the ATCo to be sure of following correct instructions and reconfirmations. **Interpredictability** – KLM-CREW reconfirms its plan with ATCo, so that ATCo would be able to guide KLM safely and effectively. **CG** – KLM attempts to re-confirm CG regarding taxi instructions. Coordination device – **signalling** – direct reconfirmation of plans.	**KLM-CREW** P4 → A12 A12 → E12	$f^{r}_{KLM-CREW}$ (plan(P4)) $[\sigma^{KLM-CREW}_{t12,ATCO}; \sigma^{ATCO}_{t12,KLM-CREW}$ $= f^{mi}_{KLM-CREW,ATCO}$(reconfirming plan(P4)) =[plan(P4) ; expectation(E12, t12+5)

Table 5.11: Final matrix, page 6

Communication	Joint Activity	Co-ladder	MASA
t13 = 1659:32.2 (ATCo) – Negative, negative, taxi straight ahead -ah- up to the end of the runway and make backtrack. (A13)	**Interdependence** – ATCo repeats the correct taxi instructions to the KLM-CREW, working to achieve the same goal. **Interpredictability** – ATCo expects KLM-CREW to acknowledge the repeated taxi instructions. ATCo repeats plan to enable predictability. **CG** – ATCo attempts to re-establish CG regarding taxi instructions with KLM-CREW. **Directability** – Repeat correct instructions through direct radio. Coordination costs – time, over (extra) communication. **Coordination breakdown** – detected by ATCo with KLM – It is a breakdown because of **language** – misunderstanding the intent of others.	**ATCo** P5 $\xrightarrow{A12}$ A13 A13 → E13	f^{r}_{ATCO}(plan(P5), $\sigma^{KLM-CREW}_{t12,ATCO}$) [$\sigma^{ATCO}_{t13,KLM-CREW}$; $\sigma^{KLM-CREW}_{t13,ATCO}$] = $f^{mi}_{KLM-CREW,ATCO}$(repeat plan(P5)) = [plan(P5) ; expectation(E13, t13+5)]

Table 5.12: Final matrix, page 7

Communication	Joint Activity	Co-ladder	MASA
t14 = 1659:39.9 (KLM-CREW) – Okay, sir. (A14)	**Interpredictability** – KLM-CREW confirms that it's going to follow plan P5. **CG** – ATCo is now aware that KLM-CREW is aware of ATCo's (correct) taxi instructions. KLM-CREW and ATCo have CG. PA-CREW is also aware of the plan KLM is following.	**KLM-CREW** P4 $\xrightarrow{A13}$ An4 An4 → P5 P5 → A14	$f^{r}_{KLM-CREW}$ (plan(P4), $\sigma^{ATCO}_{t13,KLM-CREW}$) $\sigma^{KLM-CREW}_{t14,KLM-CREW}$ = plan(P5), not(plan(P4)) $f^{r}_{KLM-CREW}$(plan(P5)) $\sigma^{KLM-CREW}_{t14,ATCO}$ = $f^{mi}_{ATCO,KLM-CREW}$(ack plan(P5)) =plan(P5) Also, $\sigma^{KLM-CREW}_{t14,PA-CREW}$ = plan(P5) $\sigma^{KLM-CREW}_{t14,KLM-CREW}$ = plan(P5), intent(plan(P5), backtrack till end, t14 + 120)

Table 5.13: Final matrix, page 8

Communication	Joint Activity	Co-ladder	MASA
t15 = 1701:50.7 (PA-CREW) – Tenerife, the Clipper 1736. (A15) t16 = 1702:01.8 (ATCo) – Clipper 1736, Tenerife. (A16)	PA establishes communication with TNR ATC to engage in Joint Activity – start coordination phase - **Intention** – to work together to achieve and maintain goals like safe & efficient air/ground operations. **Interdependence** – need to establish first contact required by aviation protocol to start executing operations. **Interpredictability** – initial contact is established between agents through communication and acknowledgement. **CG** – All the agents are required to follow aviation protocol and all of them know that the others would do so. The agents should be aware that the contact is established. ATCo is also aware of PA's goal to takeoff after KLM because of extensive delay and PA aircraft being stuck behind KLM aircraft. **Directability** – instructions through direct radio communications. Coordination device – '**convention**'.	**PA-CREW** G4 & G5 → P6 P6 → A15 A15 → E15 **ATCo** G3 → P7 P7 $\xrightarrow{A15}$ A16 A16 → E16	$\sigma^{PA-CREW}_{t15,PA-CREW}$ = goal(G4), goal(G5) $f^{r}_{PA-CREW}$(goal(G4), goal(G5)) $\sigma^{PA-CREW}_{t15,PA-CREW}$ = plan(P6) $f^{r}_{PA-CREW}$(plan(P6)) $[\sigma^{PA-CREW}_{t15,ATCO};\sigma^{ATCO}_{t15,PA-CREW}]$ = $f^{mi}_{ATCO,KLM-CREW}$(contact request) =[contact requested ; expectation(E15, t15+10)] $\sigma^{ATCO}_{t2,ATCO}$ = goal(G3) f^{r}_{ATCO} = (goal(G3), observed(KLM aircraft)) $\sigma^{ATCO}_{t2,ATCO}$ = plan(P2) $\sigma^{PA-CREW}_{t16,ATCO}$ = goal(G4),goal(G3) f^{r}_{ATCO}(plan(P2), contact requested) $[\sigma^{ATCO}_{t16,PA-CREW};\sigma^{PA-CREW}_{t16,ATCO}]$ = $f^{mi}_{KLM-CREW,ATCO}$(contact ack) =[contact established ; contact established, expectation(E16, t16+5)]

Table 5.14: Final matrix, page 9

Communication	Joint Activity	Co-ladder	MASA
t17 = 1702:03.6 (PA0CREW) – Ah - we were instructed to contact you and also to taxi down the runway, is that correct? (A17)	**Interdependence** – crew needs to obtain taxi clearance and instructions and ATCo needs to know crew's plan. **Interpredictability** – PA-CREW sharing plans and intents. PA expects acknowle--dgement and taxi instructions according to aviation protocol. **CG** – ATCo now knows PA's plans.	**PA-CREW** P6 → A17 A17 → E17	$f^{r}_{PA-CREW}$(plan(P6), contact established) $[\sigma^{PA-CREW}_{t17,ATCO};\sigma^{ATCO}_{t17,PA-CREW}]$ = $f^{mi}_{KLM-CREW}$(request taxi clearance, plan(P6)) = [requested taxi clearance, plan(P6) ; expectation(E17, t17+5)]
t18 = 1702:08.4 (ATCo) – Affirmative, taxi into the runway and – ah - leave the runway third, third to your left. (A18)	**Interdependence** – ATCo provides instructions and clearance, as per requested by PA, according to their plan. PA needs ATCo to provide specific instructions to taxi. **Interpredictability** – ATCo shared taxi plans with PA. ATCo expects acknowledgement for taxi instructions from PA. **CG** – PA now knows that they are cleared to taxi and have obtained exact taxi instructions. ATCo and PA-CREW also know that KLM aircraft has to start taxi first and then PA will follow (because of airport space restrictions).	**ATCo** P7 $\xrightarrow{A17}$ An5 An5 → P8 P8 → A18 A18 → E18	f^{r}_{ATCO}(plan(P7),plan(P6), requested taxi clearance) $\sigma^{ATCO}_{t18,ATCO}$ = plan(P8) f^{r}_{ATCO}(plan(P8)) $[\sigma^{ATCO}_{t18,PA-CREW};\sigma^{PA-CREW}_{t18,ATCO}]$ = $f^{mi}_{PA-CREW,ATCO}$(grant taxi clearance, plan(P8)) =[granted taxi clearance, plan(P8) ; expectation(E18, t18+5)]

Table 5.15: Final matrix, page 10

Communication	Joint Activity	Co-ladder	MASA
t19 = PA begins taxi down the runway behind KLM (A19) t19 = 1702:16.4 (PA) – Third to the left, okay. (A20) {1702:18.4 (PA) – Third he said.}	**Interpredictability** – PA-CREW confirms to ATCo that they are going to follow plan P8. **CG** – ATCo is now aware that PA-CREW is aware of ATCo's taxi instructions to exit at C3.	**PA-CREW** P8 $\xrightarrow{A18}$ A19 & A20	$f^{r}_{PA-CREW}$(granted taxi clearance) $\sigma^{PA-CREW}_{t19,PA-CREW}$ = position(entering runway) $f^{r}_{PA-CREW}$(plan(P8)) $\sigma^{PA-CREW}_{t19,PA-CREW}$ = plan(P8), intent(plan(P8), turn left at C3, 0.8, t19+30) $\sigma^{PA-CREW}_{t19,ATCO}$ = $f^{mi}_{PA-CREW,ATCO}$(ack taxi instructions) = plan(P8)
t20 = VISIBILITY DROP <500m, event for all agents. (Ev1)			
t21 = 1702:20.6 (ATCo) – [Th]ird one to your left. (A21)	**Interpredictability** – ATCo repeats the exact taxi instructions to ensure PA's predictable behaviour. **CG** – ATCo is repeating the taxi instructions for clarification. Sustaining CG by clarification. This also maybe because ATCo experienced confusion with KLM regarding the same instructions.	**ATCo** P8 $\xrightarrow{A20}$ A21	f^{r}_{ATCO}(plan(P8), $\sigma^{PA-CREW}_{t19,ATCO}$) [$\sigma^{ATCO}_{t21,PA-CREW}$] = $f^{mi}_{ATCO,PA-CREW}$(repeat plan(P8)) = [plan(P8)] $\sigma^{PA-CREW}_{t21,PA-CREW}$ = plan(P8), intent(plan(P8), turn left at C3, 0.4, t21+25)

Table 5.16: Final matrix, page 11

Communication	Joint Activity	Co-ladder	MASA
Internal, t22 - {1702:21.9 (PA) – I think he said first. 1702:26.4 (PA) – I'll ask him again. 1702:32.2 (PA) – Left turn.}	- Internal comm - **Coordination costs** – extra time and communication. **Interdependence** – the need to reconfirm with ATCo. **CG** - PA-CREW is unsure of the plan now and CG is compromised but ATCo doesn't know this.	-	$\sigma^{PA-CREW}_{t22,PA-CREW}$ = intent(reconfirm plan(P8), t22+15)
Internal, t23 - {1702:33.1 (PA) – I don't think they have takeoff minimums anywhere right now.} (A22)	**CG** – updating CG within the PA-CREW as visibility drops.	**PA-CREW** Ev1 → An6 An6 → P8 P8 → A22	$f^{r}_{PA-CREW}$(plan(P8), event(Ev1)) $[\sigma^{PA-CREW}_{t23.PA-CREW}]$ = $f^{oi}_{PA-CREW,TNR}$(visibility(low)) = [belief(no runway minimums)]
t24 = 1702:49.8 (ATCo) – KLM 4805, how many taxiway – ah – did you pass? (A23)	**Interdependence** – ATCo needs to know KLM's position to plan further. Absence of ground radar makes this interdependency very crucial. Also, ATCo has no visual contact with the aircraft. **Interpredictability** – Expect KLM to report their exact position on the runway. **CG** – Updating CG by requesting latest position report from KLM. Coordination choreography – **signalling** – position update required, directly requested through radio.	**ATCo** P5 → A23 A23 → E23	f^{r}_{ATCO}(plan(P5), information decay of ~2min) $[\sigma^{ATCO}_{t24,KLM-CREW};\sigma^{KLM-CREW}_{t24,ATCO}]$ = $f^{mi}_{ATCO,KLM-CREW}$(request position) = [requested position, expectation(E23, t24+5)]

Table 5.17: Final matrix, page 12

Communication	Joint Activity	Co-ladder	MASA
t25 = 1702:55.6 (KLM) – I think we just passed Charlie 4 now. (A24)	**Interpredictability** – KLM reports their position to enable ATCo to plan further. KLM expects a response to this communication. **CG** – ATCo now knows KLM's latest position. CG is maintained and updated.	**KLM-CREW** P5 $\xrightarrow{A23}$ A24 A24 → E24	$f^{r}_{KLM-CREW}$(plan(P5), requested position) $[\sigma^{KLM-CREW}_{t25,ATCO};\sigma^{ATCO}_{t25,KLM-CREW}]$ $= f^{mi}_{ATCO,KLM-CREW}$(position(KLM, past C4)) = [position(KLM, past C4) ; expectation(E24, t24+5)]
t26 = 1702:50.9 (ATCo) – Okay… at the end of the runway make 180 [degree turn] and report – ah – ready – ah – for ATC clearance. (A25)	**Interdependence** – As KLM has passed the last taxiway, KLM now needs further instructions which are now provided by ATCo. **Interpredictability** – ATCo provides further taxi instructions and expects acknowledgement. **CG** - renewing CG and sharing plans.	**ATCo** P5 $\xrightarrow{A24}$ An8 An8 → P9 P9 → A25 A25 → E25 **KLM-C** P5 $\xrightarrow{A25}$ An7 An7 → P13 **KLM-CREW** P5 $\xrightarrow{A25}$ An9 An9 → P9	f^{r}_{ATCO}(plan(P5), position(KLM, past C4)) $\sigma^{ATCO}_{t26,ATCO}$ = plan(P9) f^{r}_{ATCO}(plan(P9)) $[\sigma^{ATCO}_{t26,KLM-CREW};\sigma^{KLM-CREW}_{t26,ATCO}]$ $= f^{mi}_{KLM-CREW,ATCO}$(plan(P9)) = [plan(P9) ; expectation(E25, t26+20)] ——— $\sigma^{KLM-C}_{t26,KLM-C}$ = intent(plan(P13), turn 180 and takeoff, t26+15) $\sigma^{KLM-C}_{t26,KLM-C}$ = intent(plan(P13), turn 180 and report for ATC clearance, t26+15)

Table 5.18: Final matrix, page 13

Communication	Joint Activity	Co-ladder	MASA
Internal, t27 - {1703:09.3 (PA) – The first one is a 90-degree turn. 1703:11.0 (PA) – Yeah, okay. 1703:12.1 (PA) – Must be the third … I'll ask him again. 1703:14.2 (PA) – Okay. 1703:16.6 (PA) – We could probably go in, it's ah… 1703:19.1 (PA) – You gotta make a 90 degree turn. 1703:21.6 (PA) – Yeah, uh. 1703:21.6 (PA) – Ninety-degree turn to get around this … this one down here, it's a 45.}	- internal comm – **Coordination costs** – extra time and communication. **Interdependence** – the need to reconfirm taxi instructions with ATCo. **CG** - Incomplete CG about the exits and plans.	-	-

Table 5.19: Final matrix, page 14

Communication	Joint Activity	Co-ladder	MASA
t28 = 1703:29.3 (PA-CREW) – Would you confirm that you want Clipper 1736 to turn left at the THIRD intersection? (A26) {1703:35.1 (PA) – One, two.}	**Interdependence** – PA-CREW is dependent on the ATCo to be sure of following correct instructions and reconfirmations. **Interpredictability** – PA-CREW reconfirms its plan with ATCo, so that ATCo would be able to guide PA safely and effectively. **CG** – PA attempts to re-confirm CG regarding taxi instructions. Coordination choreography – **signalling** – direct reconfirmation of plans.	**PA-CREW** P9 → A26 A26 → E26	$f^{r}_{PA-CREW}$(plan(P8), intent(reconfirm plan(P8))) $[\sigma^{PA-CREW}_{t28,ATCO};\sigma^{ATCO}_{t25,PA-CREW}]$ = $f^{mi}_{ATCO,PA-CREW}$(reconfirming plan(P8)) = [to be reconfirmed plan(P8) ; expectation(E26, t28+5)]
t29 = 1703:36.4 (ATCo) – The third one, sir, one, two, three, third, third one. (A27)	**Interdependence** – ATCo repeats the taxi instructions to the PA-CREW, working to achieve the same goal. **Interpredictability** – ATCo explicitly repeats the plan to ensure PA's predictable behaviour. ATCo expects KLM-CREW to acknowledge the repeated taxi instructions. **CG** – ATCo attempts to sustain CG regarding taxi instructions with PA-CREW. **Directability** – Repeat correct instructions through direct radio. **Coordination costs** – time, over (extra) communication.	**ATCo** P8 $\xrightarrow{A26}$ A27 A27 → E27	f^{r}_{ATCO}(to be reconfirmed plan(P8)) $[\sigma^{ATCO}_{t29,PA-CREW};\sigma^{PA-CREW}_{t29,ATCO}]$ $f^{mi}_{PA-CREW,ATCO}$(repeated plan(P8)) = [plan(P8) ; expectation(E27, t29+5)]

Table 5.20: Final matrix, page 15

Communication	Joint Activity	Co-ladder	MASA
{1703:38.3 (PA) – One, two (four). 1703:39.0 (PA) – Good.} t30 = 1703:39.2 (PA) – Very good, thank you. (A28)	**Interpredictability** – PA-CREW confirms that it's going to follow plan P8. **CG** – ATCo is now aware that PA crew is aware of ATCo's taxi instructions plan(P8).	**PA-CREW** P8 $\xrightarrow{A27}$ A28	$f^{r}_{PA-CREW}$(repeated plan(P8)) $\sigma^{PA-CREW}_{t30,PA-CREW}$ = plan(P8) $f^{r}_{PA_C REW}$(plan(P8)) $\sigma^{PA-CREW}_{t30,ATCO}$ = $f^{mi}_{ATCO,PA-CREW}$(ack plan(P8)) = plan(P8) $\sigma^{PA-CREW}_{t30,PA-CREW}$ = intent(plan(P8), turn at C3, t30+15)
Internal, t31 - {1703:40.1 PA 1: That's what we need right, the third one. 1703:42.9 PA 3: Uno, dos, tres. 1703:44.0 PA 1: Uno, dos, tres. 1703:44.9 PA 3: Tres—uh—si. 1703:46.5 PA 1: Right. 1703:47.6 PA 3: We'll make it yet.}	This part of internal communication shows that the PA-CREW is sure of taking the THIRD exit (C3).	-	-

Table 5.21: Final matrix, page 16

Communication	Joint Activity	Co-ladder	MASA
t32 = 1703:47.6 (ATCo) - ...er 7136 [sic] report leaving the runway. (A29)	**Interdependence** – ATCo needs to know from PA when they're off the runway because of KLM takeoff. **Interpredictability** – ATCo instructs PA to report when they take th C3 exit and leave the runway. ATCo expects them to report when they are off the runway. **CG** – ATCo attempts to sustain CG regarding the position (current and future) position of PA aircraft.	**ATCo** P8 $\xrightarrow{A28}$ A29 A29 → E29	f^{r}_{ATCO}(plan(P8)) $[\sigma^{ATCO}_{t32,PA-CREW};\sigma^{PA-CREW}_{t32,ATCO}]$ $f^{mi}_{PA-CREW,ATCO}$(report when position(off runway)) = [report when position(off runway); expectation(E29, t32+60)]
t33 = 1 minute long, PA engineer's taxi check. And also, take off and departure briefing.	-	-	-

Table 5.22: Final matrix, page 17

Communication	Joint Activity	Co-ladder	MASA
t34 = 1704:58.2 (ATCo) - [KLM] 8705 [sic] and Clipper 1736, for your information, the centerline lighting is out of service. (A30) [APP transmission is readable but slightly broken]	**Interdependence** – KLM and PA crews are both dependent on the ATCo for airport related information. **Interpredictablity** – Such information from ATCo increases the predictability of the crews in terms of safe airport operations. **CG** - ATCo is attempting to update the CG of the crews regarding runway lighting. Also because the visibility is extremely low. Coordination choreography – **signalling** – direct communication of crucial information through direct radio.	**ATCo** G3 → P10 P10 → A30 A30 → E30	f^{r}_{ATCO}(goal(G3)) $\sigma^{ATCO}_{t33,ATCO}$ = plan(P10) f^{r}_{ATCO}(plan(P10)) $[\sigma^{ATCO}_{t33,PA-CREW};\sigma^{PA-CREW}_{t33,ATCO}]$ = $f^{mi}_{ATCO,PA-CREW}$(no runway lights) = [no runway lights ; expectation(E30, t33+5)] & $[\sigma^{ATCO}_{t33,KLM-CREW};\sigma^{KLM-CREW}_{t33,ATCO}]$ = $f^{mi}_{ATCO,KLM-CREW}$(no runway lights) = [no runway lights ; expectation(E30, t33+5)]
t35 = 1705:05.8 (KLM-CREW) - I copied that. (A31) t36 = 1705:07.7 (PA-CREW) - Clipper 1736. (A32)	**Interpredictability** – Crew acknowledge received information according to protocol. Crews now have predictability for airport properties. **CG** – The ATCo and the crews have CG regarding runway centre lights.	KLM-CREW P9 $\xrightarrow{A30}$ A31 PA-CREW P8 $\xrightarrow{A30}$ A32	$f^{r}_{KLM-CREW}$(no runway lights) $\sigma^{KLM-CREW}_{t35,ATCO}$ = $f^{mi}_{ATCO,KLM-CREW}$(ack no runway lights) = knows(no runway lights) $\sigma^{PA-CREW}_{t36,ATCO}$ = $f^{mi}_{ATCO,PA-CREW}$(ack no runway lights) = knows(no runway lights)

Table 5.23: Final matrix, page 18

Communication	Joint Activity	Co-ladder	MASA
Internal, t37 - {1705:09.6 PA 1: We got centerline markings (only) [could be "don't we"] they count the same thing as ... we need 800 meters if you don't have that centerline ... I read that on the back (of this) just a while ago. 1705:22.0 PA 1: That's two. 1705:23.5 PA 3: Yeah, that's 45 [degrees] there. 1705:25.7 PA 1: Yeah. 1705:26.5 PA 2: That's this one right here. 1705:27.2 PA 1: [Yeah], I know. 1705:28.1 PA 3: Okay. 1705:28.5 PA 3: Next one is almost a 45, huh, yeah. 1705:30.6 PA 1: But it goes... 1705:32.4 PA 1: Yeah, but it goes ... ahead, I think (it's) gonna put us on (the) taxiway. 1705:35.9 PA 3: Yeah, just a little bit, yeah. 1705:39.8 PA ?: Okay, for sure. 1705:40.0 PA 2: Maybe he, maybe he counts these (are) three. 1705:40.0 PA ?: Huh. 1705:44.8 PA ?: I like this.}	Coordination breakdown – undetected – **Environment and technology** – PA-CREW does not have good knowledge of TNR as it a completely new environment. ATCo does not have ground radar to detect this breakdown.	-	-

Table 5.24: Final matrix, page 19

Communication	Joint Activity	Co-ladder	MASA
t37 = KLM aircraft takes 180 °turn at the end of the runway. (A33) Internal, t37 – (KLM-CREW) = KLM Captain initiates takeoff (even before ATC or takeoff clearance has been requested). (A34)	**Interpredictability** – KLM-F states the next part of the plan that the KLM-CREW needs to follow enabling predictability. **CG** – There is a loss of CG since all crew expects all crew to follow aviation protocol to takeoff safely but the KLM-C forgets ATC and takeoff clearance. KLM-F detects this failure and attempts to repair and re-establish CG by stating what is to be done next according to plans and protocols. Coordination choreography – **signalling** – KLM-F can directly communicate with KLM-C in the event that he detects an anomaly.	**KLM-C** P13 → A33 P13 $\xrightarrow{A33}$ A34	$\sigma^{KLM-CREW}_{t37,KLM-CREW}$ = position(turned 180) f^{r}_{KLM-C}(plan(P13), position(turned 180))
t38 = 1705:41.5 (KLM-F): Wait a minute, we don't have an ATC clearance. (A35)	**Coordination breakdown** – detected – a. **Memory** – KLM Capt. forgetting steps in takeoff protocol, requesting ATC clearance followed by requesting takeoff clearance; detected by the KLM First Officer. b. **Individual differences**; i.Different comfort levels with non-standard situations – KLM Captain was in a hurry to takeoff ASAP so as not to exceed the strict Dutch duty limits recently imposed. ii. Personality – Authoritative and arrogant. iii. Unprofessional behaviour.	**KLM-F** P9 $\xrightarrow{A34}$ A35	$[\sigma^{KLM-C}_{t38,KLM-F}]$ = $f^{oi}_{KLM-F,KLM-C}$(initiate takeoff) = [initiated takeoff]

Table 5.25: Final matrix, page 20

Communication	Joint Activity	Co-ladder	MASA
Internal, t39 - 1705.42.0 (KLM-C): No, I know that. Go ahead, ask. (A36)	**Interdependence** – KLM-CREW has to depend on ATCo to get ATC clearance. **Interpredictability** - KLM-C stating his intention to follow plan P9, enabling predictability. **CG** – CG is re-established. KLM-C acknowledges the need to ask for ATC clearance according to plan.	**KLM-C** P13 $\xrightarrow{A35}$ An10 An10 → P9 P9 → A36 A36 → E36	$f^{r}_{KLM-C}(\text{plan(P13)}, \sigma^{KLM-F}_{t38,KLM-C})$ $[\sigma^{KLM-C}_{t39,KLM-F};\sigma^{KLM-F}_{t39,KLM-C}]$ $= f^{mi}_{KLM-F,KLM-C}$(ack interruption) = [plan(P9) ; expectation(E36, t39+2)]
t40 = 1705:44.6 (KLM-CREW): Uh, the KLM 4805 is now ready for takeoff and we're waiting for our ATC clearance. (A37)	**Interdependence** – KLM-CREW is dependent on the ATCo for ATC clearance. **Interpredictability** – KLM-CREW expects ATCo to provide them with ATC clearance. KLM-CREW reports ready for ATC clearance as instructed by ATCo earlier, enabling interpredictability. **CG** - ATCo now knows that KLM has turned 180 at runway end and is ready for ATC clearance and for takeoff.	**KLM-CREW** P9 $\xrightarrow{A36}$ A37 A37 → E37	$f^{r}_{KLM-CREW}(\text{plan(P9)})$ $[\sigma^{KLM-CREW}_{t40,ATCO};\sigma^{ATCO}_{t40,KLM-CREW}]$ $= f^{mi}_{ATCO,KLM-CREW}$(request ATC clearance) = [requested ATC clearace ; expectation(E37, t40+5)]

Table 5.26: Final matrix, page 21

Communication	Joint Activity	Co-ladder	MASA
			f^{r}_{ATCO}(plan(P9), requested ATC clearance)
t41 = 1705:53.4 (ATCo): KLM 8705 [sic] uh you are cleared to the Papa beacon. Climb to and maintain flight level 90 ... right turn after takeoff proceed with heading 040 until intercep- -ting the 325 radial from Las Palmas VOR. (A38)	**Interpredictability** – ATCo provides KLM with ATC clearance and expects the crew to acknowledge these instructions. **CG** - KLM-CREW now has ATC clearance and ATCo knows that KLM-CREW knows that they have ATC clearance. ATCo also knows that KLM is ready for takeoff.	**ATCo** P9 $\xrightarrow{A37}$ An11 An11 → P11 P11 → A38 A38 → E38	$[\sigma^{ATCO}_{t41,KLM-CREW};\sigma^{ATCO}_{t41,KLM-CREW}]$ $= f^{mi}_{KLM-F,KLM-C}$(grant ATC clearance, plan(P11)) = [granted ATC clearance, granted takeoff clearance, plan(P11) ; expectation(E38, t41+5)] ——— $f^{r}_{KLM-CREW}$(plan(P9), granted ATC clearance, granted takeoff clearance, plan(P11))
t42 = 1706:09.6 (KLM-CREW): Ah, roger, sir, we're cleared to the Papa beacon flight level 90, right turn out 040 until intercepting the 325, and we're now (at takeoff). (A39)	**Coordination breakdown** – undetected – **Language** – **a.** Using non-standard terminology of incorrect format: "we are not at takeoff" (takeoff position or taking off or ready for takeoff?) **b.** Saying one thing and meaning something else: Saying that we are ready for takeoff now but meaning that we are going to takeoff now. **c.** Misunderstanding the intent of others.	**KLM-CREW** P9 $\xrightarrow{A38}$ An12 An12 → P11 P11 → A39 & A40 A40 → E40	$\sigma^{KLM-CREW}_{t42,KLM-CREW}$ = plan(P11), intent(plan(P11), takeoff, t42+2) $\sigma^{KLM-CREW}_{t43,KLM-CREW}$ = position(taking off) $[\sigma^{KLM-CREW}_{t42,ATCO};\sigma^{ATCO}_{t42,KLM-CREW}]$ $= f^{mi}_{ATCO,KLM-CREW}$(plan(P11), position(taking off)) = [plan(P11), position(at takeoff) ; expectation(E40, t42+20)]

Table 5.27: Final matrix, page 22

Communication	Joint Activity	Co-ladder	MASA
Internal, t43 (A40) - {1706:11.08: [Brakes of KLM 4805 are released.] (A40a) 1706:12.25 (KLM-C): Let's go … check thrust. (A40b) 1706:14.00: [Sound of engines starting to accelerate.] (A40c)}	**CG** – KLM loses CG with other agents because they forget protocol and the other agents don't know this. **Coordination breakdown** - Undetected – **Attention** – KLM-CREW forgets takeoff clearance as a whole. Takeoff is initiated after receiving ATC clearance.	-	-
t44 = 1706:18.19 (ATCo): Okay. (A41)	**CG** – ATCo does not know that KLM is initiating takeoff. According to protocol, KLM should also ask for takeoff clearance. ATCo probably thinks KLM is only reporting ready for takeoff. KLM thinks ATCo says "Okay" for takeoff.	**ATCo** P11 $\xrightarrow{A39}$ A41	f^{r}_{ATCO}(plan(P11), $\sigma^{KLM-CREW}_{t42,ATCO}$) $\sigma^{ATCO}_{t44,KLM-CREW}$ = $f^{mi}_{ATCO,KLM-CREW}$(ack) = [knows(KLM, position(taking off)] Also, $\sigma^{KLM-CREW}_{t42,PA-CREW}$ = position(taking off)

Table 5.28: Final matrix, page 23

Communication	Joint Activity	Co-ladder	MASA
	Interdependence – PA-CREW depends on ATCo to not clear KLM for takeoff as they are still on the runway. **Interpredictability** – ATCo expects KLM to wait for takeoff clearance. PA-CREW explicitly declare their position on the runway so all agents have interpredict--ability. ATCo asks KLM to standby for takeoff, enabling predictability that they do not takeoff without takeoff clearance.		
The following is NOT heard in the KLM cockpit due to two agents speaking simultaneously on the R/T. t45 = 1706:20.08 (ATCo): Stand by for takeoff ... I will call you. (A42)	**CG** – As KLM-CREW cannot hear this interaction, they do not have a CG update regarding PA's position. PA knows KLM is ready for takeoff and hence, declared their position on the runway. ATCo knows that PA is on the runway and CG has been updated between PA and ATCo.	**ATCo** P11 $\xrightarrow{A39}$ A42 A42 → E42	$[\sigma^{ATCO}_{t45,KLM-CREW};\sigma^{KLM-CREW}_{t42,ATCO}]$ $= f_{ATCO,KLM-CREW}$(standby for takeoff) = [- ; expectation(E42, t45+10)] $f^{r}_{PA-CREW}(\sigma^{KLM-CREW}_{t42,PA-CREW})$
Internal – PA-CREW - : No, uh. ~ 1706:20.08 (PA-CREW): And we are still taxiing down the runway, the Clipper 1736. (A43)	Coordination device – **signalling** – PA-CREW explicitly made their position clear. **Directability** – PA-CREW's explicit declaration after hearing KLM's "now at takeoff" message. **Coordination breakdown** – Undetected – Environment & Technology – KLM couldn't hear ATCo's message to stand-by and neither PA's position declaration on the runway because they spoke simultaneously and the R/T produced a shrill noise in the KLM cockpit.	**PA-CREW** P8 $\xrightarrow{A41}$ A43 A43 → E43	$[\sigma^{PA-CREW}_{t45,ATCO};\sigma^{ATCO}_{t45,PA-CREW}]$ $= f^{mi}_{ATCO,PA-CREW}$(report position(on runway)) = [position(on runway) ; expectation(E43, t45+5)]

Table 5.29: Final matrix, page 24

Communication	Joint Activity	Co-ladder	MASA
t46 = 1706:25.47 (ATCo): Ah— Papa Alpha 1736 report runway clear. (A44) t47 = 1706:25.59 (PA-CREW): Okay, we'll report when we're clear. (A45) t48 = 1706:31.69 (ATCo): Thank you. (A46)	**Interdependence** – ATCo is dependent on PA-CREW to report their position when they are clear off the runway. **Interpredictability** – ATCo expects PA-CREW to report when they are off the runway. PA-crew says they will report when they are off the runway. PA-CREW expects no takeoff to be allowed until they are on the runway. **CG** - ATCo knows PA is on the runway and PA knows that ATCo knows they are on the runway. PA and ATCo also know that PA will report when clear off the runway. This communication can be heard is the KLM cockpit and is against all expectation.	**ATCo** P8 $\xrightarrow{\underline{A43}}$ A44 A44 → E44 **PA-CREW** P8 $\xrightarrow{\underline{A44}}$ A45 A45 → E45 **ATCo** P8 $\xrightarrow{\underline{A45}}$ A46	f^{r}_{ATCO}(plan(P8), position(on runway)) $[\sigma^{ATCO}_{t46,PA-CREW};\sigma^{PA-CREW}_{t46,ATCO}]$ $=f^{mi}_{ATCO,PA-CREW}$(report when position(off runway)) =[report when position(off runway); expectation(E44, t46+5)] ——— $f^{r}_{PA-CREW}$(report when position (off runway), plan(P8)) $[\sigma^{PA-CREW}_{t47,ATCO};\sigma^{ATCO}_{t47,PA-CREW}]$ $=f^{mi}_{ATCO,PA-CREW}$(ack request to report position(off runway)) =[belief(report when position(off runway); expectation(E45, t47+5)] ———- f^{r}_{ATCO}(plan(P8), $\sigma^{PA-CREW}_{t47,ATCO}$) $[\sigma^{ATCO}_{t48,PA-CREW}$(ack the acknowledgement of request) =[knows(PA-CREW, report when position(off runway))]

Table 5.30: Final matrix, page 25

Communication	Joint Activity	Co-ladder	MASA
Internal, t49 - {1706:32.43 KLM 3: Is he not clear, then? 1706:34.10 KLM 1: What do you say? 1706:34.15 PA ?: Yup. 1706:34.70 KLM 3: Is he not clear, that Pan American? 1706:35.70 KLM 1: Oh, yes. [emphatically] -IMPACT occurs 13s after this comm-	**CG** – KLM-CREW now realises that PA is on the runway, right in front of them. **Coordination breakdown** – detected – Expectation – KLM-CREW expected the runway to be clear for takeoff, expect PA to already have exited. After hearing the previous communication, KLM-CREW realises that it is too late.	**KLM-CREW** P11 $\xrightarrow{A44,\,A45}$ An13 An13 → S1	$f^{r}_{KLM-CREW}$(PA report when position(off runway)) $[\sigma^{PA-CREW}_{t49,KLM-CREW}$ = [position (on runway)]
KLM & PA have visual contact while head-on. (Ev2) t50 = KLM-C attempts to liftoff (over PA). (A47) t50 = PA-C attempts to go off the runway (to avoid KLM). (A48) t51 = A49 = IMPACT	**CG** – PA and KLM crews now have perfect CG and both attempt to avoid the collision.	**KLM-CREW** S2 → A47 **PA-CREW** Ev2 → A48	$[\sigma^{KLM-CREW}_{t50,PA-CREW};\sigma^{PA-CREW}_{t50,KLM-CREW}]$ = $f^{oi}_{PA-CREW,KLM-CREW}$(visual contact) = [position(head-on collision) ; position(head-on collision)] $[\sigma^{KLM-CREW}_{t51,KLM-CREW};\sigma^{PA-CREW}_{t51,PA-CREW}]$ =[attempt to liftoff ; attempt to go off runway]

Table 5.31: Final matrix, page 26

The comprehensively depicted final matrix does not solely concentrate on the implementation of the three frameworks but mainly demonstrates the deep-dive analysis and understanding of the accident case at every time step that can be obtained using the three frameworks in complementation. The final matrix provides an abstract view of the coordination processes in this interaction along with a specific flow-chart to understand coordination and communication of agents. The modelling of all these elements with a mathematical structure provides a formalization of the human cognition and interaction within this sociotechnical setting. This analysis in-turn helps to recognize certain important coordination mechanisms pertaining to common ground and how agents can lose, identify the loss and repair the loss of common ground. A further step of modelling and simulation can also provide a good basis for the validation of the same.

To better understand common ground, we have to understand how situation awareness plays a role when the agents are coordinating. Every conscious agent in a system has a certain awareness about itself, its environment and other agents too. As explained before, common ground is achieved between two or more agents if their awareness regarding a certain state is "common" or congruent. Hence, understanding the dynamics of the relations of situation awareness among agents is the next important step in identifying the specific coordination mechanisms that enable good common ground. The following section presents the same.

5.5. Analysis of the coordination model

While analysing the model of coordination (Tables 5.6 to 5.31) to gain an understanding of **common ground**, it was felt prudent to consider it from three perspectives; CG that is updated & maintained at every time step, CG that must be maintained and monitored over a period of time and CG that is lost and should be repaired. The following table shows how and what common ground is updated at every time step. The table also shows the states regarding which agents should maintain, monitor or update CG as time passes. It also shows the loss of common ground (both detected and undetected) at each time step, if any. The criteria for which states the agents must maintain CG was decided based on multiple factors;

- Standard aviation protocol dictates all agents to acknowledge all communication using appropriate terminology.
- Agents intent to follow a plan unless there is an update for another plan or a new plan, rendering the old plan obsolete.
- Controllers intend to know the dynamic states of aircraft with timely updates.
- Aircraft crews must intend to know if the controller knows their position (after they report it); this is a second level awareness on the part of the crews.
- In certain situations, it is also crucial for the controller to know that the aircraft crew knows that the controller knows their report of a dynamic state;

this is a third level of awareness of the part of the controller.

- Due to safety concerns and efficient operability, it is also prudent for agents to maintain common ground about certain environmental characteristics (like level of visibility).

Several important properties of this table have also been listed here;

1. Agents maintain common ground regarding higher-order states, like each other's goals, throughout all the time steps and hence, these CG aspects have been identified at the start and remain true throughout the study. The agents need not seek to maintain/monitor this CG unless a major stance change occurs.

2. The first column shows the communication from the official transcript of the case and each time step is only depicted by the time number and the activity number.

3. The second column only shows the states regarding which agents i and k have maintained common ground at that time. Hence, this column primarily depicts all the CG updates that occur at every time step.

4. The third column shows the states that the agents are (supposed to be) monitoring to perform this joint activity. Many CG states start at a certain time step and end eventually. These states have been identified at the time point where they "start" and hold true for every time step unless identified with a ¬(CG state) at a particular time step.

5. The last column shows the loss (detected and undetected) of common ground at every time step. A CG loss once identified as "undetected" stays that way through all subsequent time steps until it is identified as "detected".

6. Usually when a SA relation is defined by "knows(abc)", it refers to a second degree of awareness level. While it can also refer to the third degree of awareness, such instances have been pointed out in the following table.

Time	CG maintained and updated	CG that agents are (supposed to) monitor and sustain	CG loss
t1, A1	$S^{ATCO}_{KLM-CREW}$ = goal(G3) $S^{KLM-CREW}_{ATCO}$ = contact requested		
t2, A2	$S^{KLM-CREW}_{ATCO}$ = goal(G1), goal(G2) $S^{KLM-CREW}_{ATCO}$ = knows(contact requested) $S^{ATCO}_{KLM-CREW}$ = contact acknowledged	$S^{KLM-CREW}_{ATCO}$ = contact established $S^{ATCO}_{KLM-CREW}$ = contact established	
t3, A3	$S^{KLM-CREW}_{ATCO}$ = plan(P1) $S^{KLM-CREW}_{ATCO}$ = requested taxi clearance $S^{KLM-CREW}_{ATCO}$ = knows(contact acknowledged)		
t4, A4	$S^{ATCO}_{KLM-CREW}$ = knows(plan(P1)) $S^{ATCO}_{KLM-CREW}$ = knows(requested taxi clearance) $S^{ATCO}_{KLM-CREW}$ = granted taxi clearance	$S^{ATCO}_{KLM-CREW}$ = plan(P4) $S^{KLM-CREW}_{ATCO}$ = knows(plan(P3))	Undetected - $S^{ATCO}_{KLM-CREW}$ = plan(P4), plan(P3)

Table 5.33: Common Ground analysis, page 1

Time	CG maintained and updated	CG that agents are (supposed to) monitor and sustain	CG loss
t5, A5 t6, A6	$S_{ATCO}^{KLM-CREW}$ = knows(granted taxi clearance) $S_{ATCO}^{KLM-CREW}$ = position (entering runway) $S_{ATCO}^{KLM-CREW}$ = plan(P4)	$S_{ATCO}^{KLM-CREW}$ = position (entering runway) $S_{KLM-CREW}^{TNR}$ = position (entering runway) $S_{KLM-CREW}^{ATCO}$ = knows(position (entering runway))	Detected by ATCo - $S_{ATCO}^{KLM-CREW}$ = knows(plan(P4)), knows(plan(P3))
t7, A7	$S_{KLM-CREW}^{ATCO}$ = knows(position (entering runway))	$S_{ATCO}^{KLM-CREW}$ = knows(plan(P5))	Undetected - $S_{KLM-CREW}^{ATCO}$ = plan(P4), plan(P5)
t8, A8			Undetected - $S_{ATCO}^{KLM-CREW}$ = knows(plan(P5), knows(plan(P4))
t9, A9 t10, A10	$S_{ATCO}^{KLM-CREW}$ = position(on runway)	$\neg S_{ATCO}^{KLM-CREW}$ = position(entering runway) $\neg S_{KLM-CREW}^{TNR}$ = position(entering runway) $S_{ATCO}^{KLM-CREW}$ = position(on runway) $S_{KLM-CREW}^{ATCO}$ = knows(position (on runway)) $S_{KLM-CREW}^{TNR}$ = position(on runway)	

Table 5.35: Common Ground analysis, page 2

Time	CG maintained and updated	CG that agents are (supposed to) monitor and sustain	CG loss
t11, A11	$S^{ATCO}_{KLM-CREW}$ = knows(position (on runway)	$\neg S^{ATCO}_{KLM-CREW}$ = knows(position (entering runway))	
t12, A12		Maintaining, $S^{ATCO}_{KLM-CREW}$ = plan(P4)	Detected by ATCo - $S^{KLM-CREW}_{ATCO}$ = knows(plan(P4)), knows(plan(P5))
t13, A13	$S^{ATCO}_{KLM-CREW}$ = plan(P5)	$\neg S^{ATCO}_{KLM-CREW}$ = plan(P4) $S^{ATCO}_{KLM-CREW}$ = plan(P5)	Detected by KLM-CREW - $S^{ATCO}_{KLM-CREW}$ = plan(P5), not plan(P4)
t14, A14	$S^{KLM-CREW}_{ATCO}$ = knows(plan(P5))		
t15, A15	$S^{ATCO}_{PA-CREW}$ = goal(G3) $S^{PA-CREW}_{ATCO}$ = contact requested		
t16, A16	$S^{PA-CREW}_{ATCO}$ = goal(G5), goal(G6) $S^{PA-CREW}_{ATCO}$ = knows(contact requested) $S^{ATCO}_{KLM-CREW}$ = contact acknowledged	$S^{PA-CREW}_{ATCO}$ = contact established $S^{ATCO}_{PA-CREW}$ = contact established	

Table 5.37: Common Ground analysis, page 3

Time	CG maintained and updated	CG that agents are (supposed to) monitor and sustain	CG loss
t17, A17	$S^{PA-CREW}_{ATCO}$ = plan(P6) $S^{PA-CREW}_{ATCO}$ = requested taxi clearance $S^{PA-CREW}_{ATCO}$ = knows(contact acknowledged)		
t18, A18	$S^{ATCO}_{PA-CREW}$ = knows(plan(P6)) $S^{ATCO}_{PA-CREW}$ = knows(requested taxi clearance) $S^{ATCO}_{PA-CREW}$ = granted taxi clearance	$S^{ATCO}_{PA-CREW}$ = plan(P8) $S^{PA-CREW}_{ATCO}$ = knows(plan(P8))	
t19, A19 & A20	$S^{PA-CREW}_{ATCO}$ = knows(plan(P8))	$S^{TNR}_{PA-CREW}$ = position(PA 747)	PA-CREW never declare when they begin taxiing or when they enter the runway - $S^{PA-CREW}_{ATCO}$ = position(PA 747)
t20, Ev1		$S^{TNR}_{KLM-CREW}$ = visibility level(low) S^{TNR}_{ATCO} = visibility level(low) $S^{TNR}_{PA-CREW}$ = visibility level(low)	Undetected - $S^{TNR}_{KLM-CREW}$ = [no runway minimums, visibility level(low)] S^{TNR}_{ATCO} = [no runway minimums, visibility level(low)] $S^{TNR}_{PA-CREW}$ = [no runway minimums; visibility level(low)]

Table 5.39: Common Ground analysis, page 4

Time	CG maintained and updated	CG that agents are (supposed to) monitor and sustain	CG loss
t21, A21	$S^{ATCO}_{PA-CREW}$ = knows(plan(P8)) This relation shows a third level awareness of the PA-CREW; PA-CREW knows that ATCO knows that PA-CREW is following plan P8.	Clarifying, $S^{PA-CREW}_{ATCO}$ = knows(plan(P8))	
t22 (PA, internal)			Undetected- $S^{ATCO}_{PA-CREW}$ = [plan(¬P8), plan(P8)]
t23 (PA, internal)	$S^{TNR}_{PA-CREW}$ = [no runway minimums, visibility level(low)]	$S^{TNR}_{PA-CREW}$ = no runway minimums	Detected by PA-CREW- $S^{TNR}_{PA-CREW}$= [no runway minimums, visibility level(low)]
t24, A23	$S^{ATCO}_{KLM-CREW}$ = requested position	Updating, $S^{KLM-CREW}_{ATCO}$ = position(on runway)	
t25, A24	$S^{TNR}_{KLM-CREW}$ = position(past C4) $S^{KLM-CREW}_{ATCO}$ = position(past C4)	$\neg S^{KLM-CREW}_{ATCO}$ = position(on runway) $\neg S^{TNR}_{KLM-CREW}$ = position(on runway) $S^{KLM-CREW}_{ATCO}$ = position(past C4) $S^{ATCO}_{KLM-CREW}$ = knows(position(past C4)) $S^{TNR}_{KLM-CREW}$ = position(past C4)	

Table 5.40: Common Ground analysis, page 5

Time	CG maintained and updated	CG that agents are (supposed to) monitor and sustain	CG loss
t26, A25	$S^{ATCO}_{KLM-CREW}$ = knows(positio n(past C4)) S^{ATCO}_{KLM-RF} = plan(P9) S^{ATCO}_{KLM-C} = plan(P13)	$\neg S^{ATCO}_{KLM-CREW}$ = knows(position (on runway)) $\neg S^{KLM-CREW}_{ATCO}$ = knows(plan(P5)) $\neg S^{ATCO}_{KLM-CREW}$ = plan(P5) S^{ATCO}_{KLM-RF} = plan(P9) S^{ATCO}_{KLM-RF} = knows(plan(P9)) S^{ATCO}_{KLM-C} = plan(P13) S^{ATCO}_{KLM-C} = knows(plan(P13))	Undetected - S^{ATCO}_{KLM-C} = [plan(P13), plan(P9)] S^{KLM-C}_{KLM-RF} = [plan(P9), plan(P13)]
t27 (PA, internal)			
t28, A26		Maintaining, $S^{ATCO}_{PA-CREW}$ = plan(P8)	
t29, A27		Clarifying, $S^{PA-CREW}_{ATCO}$ = knows(plan(P8))	
t30, A28			
t31 (PA, internal)			
t32, A29	$S^{ATCO}_{PA-CREW}$ = report position (off runway)		

Table 5.41: Common Ground analysis, page 6

Time	CG maintained and updated	CG that agents are (supposed to) monitor and sustain	CG loss
t33 - t34, A30	$S^{TNR}_{KLM-CREW}$ = no runway lights S^{TNR}_{ATCO} = no runway lights $S^{TNR}_{PA-CREW}$ = no runway lights	$S^{TNR}_{PA-CREW}$ = no runway lights $S^{TNR}_{KLM-CREW}$ = no runway lights $S^{KLM-CREW}_{ATCO}$ = knows(no runway lights) $S^{PA-CREW}_{ATCO}$ = knows(no runway lights)	
t35, A31 t36, A32	$S^{KLM-CREW}_{ATCO}$ = knows(no runway lights) $S^{PA-CREW}_{ATCO}$ = knows(no runway lights)	$\neg S^{KLM-CREW}_{ATCO}$ = knows(no runway lights) $\neg S^{PA-CREW}_{ATCO}$ = knows(no runway lights)	Undetected - S^{ATCO}_{KLM-C} = [plan(P13), plan(P9)] S^{KLM-C}_{KLM-RF} = [plan(P9), plan(P13)]
t37 (PA, internal)			Undetected - $S^{TNR}_{PA-CREW}$ = [position(in front C2), position(in front C3)]
t37, A33 t37, A34 t38, A35 (KLM, internal)	$S^{TNR}_{KLM-CREW}$ = position(turn 180) S^{KLM-RF}_{KLM-C} = interruption takeoff S^{KLM-RF}_{KLM-C} = plan(P9)	$\neg S^{TNR}_{KLM-CREW}$ = position(past C4) $S^{TNR}_{KLM-CREW}$ = position(turn 180)	Detected by KLM-RF - S^{KLM-C}_{KLM-RF} = [plan(P13), plan(P9)]
t39, A36 (KLM, internal)	S^{KLM-C}_{KLM-RF} = knows(plan(P9)		

Table 5.42: Common Ground analysis, page 7

Time	CG maintained and updated	CG that agents are (supposed to) monitor and sustain	CG loss
t40, A37	$S^{KLM-CREW}_{ATCO}$ = position(ready takeoff) $S^{KLM-CREW}_{ATCO}$ = requested ATC clearance	$\neg S^{KLM-CREW}_{ATCO}$ = position(past C4) $S^{KLM-CREW}_{ATCO}$ = position(ready takeoff)	
t41, A38	$S^{ATCO}_{KLM-CREW}$ = knows(position (ready takeoff)) $S^{ATCO}_{KLM-CREW}$ = knows(requested taxi clearance) $S^{ATCO}_{KLM-CREW}$ = granted taxi clearance $S^{ATCO}_{KLM-CREW}$ = plan(P11)	$\neg S^{ATCO}_{KLM-CREW}$ = plan(P9) $\neg S^{KLM-CREW}_{ATCO}$ = knows(plan(P9)) $S^{ATCO}_{KLM-CREW}$ = plan(P13) $\neg S^{TNR}_{KLM-CREW}$ = position(turn 180) $S^{KLM-CREW}_{ATCO}$ = knows(plan(P11))	Undetected - $S^{ATCO}_{KLM-CREW}$ = [granted ATC and takeoff clearance, granted ATC clearance]
t42, A39	$S^{KLM-CREW}_{ATCO}$ = knows(plan(P11)) $S^{KLM-CREW}_{ATCO}$ = knows(granted ATC clearance)		Undetected - $S^{KLM-CREW}_{ATCO}$ = [position(at takeoff), position(taking off)] $S^{KLM-CREW}_{PA-CREW}$ = [position(at takeoff), position(taking off)] $^{KLM-CREW}_{ATCO}$ = [knows(granted ATC clearance), knows(granted ATC and takeoff clearance)]

Table 5.43: Common Ground analysis, page 8

Time	CG maintained and updated	CG that agents are (supposed to) monitor and sustain	CG loss
t43, A40 t44, A41	$S_{KLM-CREW}^{ATCO}$ = knows(plan(P11) Level 3 SA of KLM-CREW.		Undetected - $S_{KLM-CREW}^{ATCO}$ = [knows(position (taking off), knows(position (at takeoff)]
t45, A42 & A43	$S_{PA-CREW}^{TNR}$ = position(on runway) $S_{ATCO}^{PA-CREW}$ = position(on runway)	$\neg S_{ATCO}^{KLM-CREW}$ = position(ready takeoff) $S_{ATCO}^{KLM-CREW}$ = position(standby takeoff) $S_{ATCO}^{PA-CREW}$ = position(on runway) $S_{PA-CREW}^{TNR}$ = position(on runway)	Undetected - $S_{KLM-CREW}^{PA-CREW}$ = [position(off runway), position(on runway)] $S_{ATCO}^{KLM-CREW}$ = [position(standby takeoff), position(taking off)]
t46, A44 t47, A45 t48, A46	$S_{PA-CREW}^{ATCO}$ = report when position (off runway) $S_{ATCO}^{PA-CREW}$ = knows(report when position(off runway)) $S_{PA-CREW}^{ATCO}$ = knows(report when position(off runway))		Undetected - $S_{PA-CREW}^{TNR}$ = [position(in front C2), position(in front C3)]
t49 (KLM, internal)	$S_{KLM-CREW}^{PA-CREW}$ = position(on runway)		Detected - $S_{KLM-CREW}^{PA-CREW}$ = [position(on runway), position(off runway)]
t50, A47 & A48 t51 = IMPACT	$S_{PA-CREW}^{KLM-CREW}$ = position(taking off)		Detected - $S_{PA-CREW}^{KLM-CREW}$ = [position(taking off), position(at takeoff)]

Table 5.44: Common Ground analysis, page 9

5.6. Identifying mechanisms

Based on the final matrix and the analysis of common ground; certain coordination mechanisms have been identified. These mechanisms have been enlisted based on the crucial states regarding which the agents must maintain CG to ensure effective coordination. The following **crucial states** have been recognized for this ATM case study:

- An agent's own position.
- An agent's awareness of other agent's position, in the vicinity.
- An agent's awareness of the plan to be/being followed, including the respective steps of the plan.
- An agent's awareness of another agent's awareness of the plan to be/being followed.

5.6.1. Mechanisms for identification of CG loss

Identifier	Mechanism
D1	Acknowledgement (and repeating) the plan or instructions by an agent, as per aviation protocol, usually reveals to one of the agents that CG is lost when the acknowledged plan is incorrect.
D2	Explicit confirmation of a previous plan can reveal the loss of CG to the other agent if the plan being confirmed is incorrect.
D3	The aircraft crews can hear inconsistent information in the other crews' communication with the controller and identify loss of CG. Hence, indirect identification via inference based on communicated states can help in the identification of the loss of CG.
D4	The visual observation goes against what is being expected: detection of loss of CG.
D5	An observed or communicated state does not correspond to the expected state of an agent.
D6	The intent to repeat important parts of the information without a request to do so.
D7	The intent to ask for information repetition in case of wrong terminology, illegible audio, multiple interpretations or disturbance/disconnection of radio (instances with low degree of certainty).
D8	An agent's tone of voice and "how" something is communicated (unsure communication) can lead to detection of loss of CG.
D9	Explicit discussion or reasoning within a team can also reveal inconsistencies in CG, particularly exchanges of information on stances between team members.
D10	CG loss can be identified when agents can recognize that certain information has expired.
D11	CG loss can be identified when a certain information certainty has reached a certain threshold.

Table 5.45: Mechanisms for the identification of the loss of CG

Once the mechanisms are identified, some generalizations can be made in terms of the CG loss identification mechanisms used by the controllers as opposed to the ones used by the crews. The following Table 5.46 presents the general coordination mechanisms used by specific types of agents in this case study.

CREWS	CONTROLLERS
By observation against expectation By requesting repeat of some information (plan etc.) An agent's tone of voice Team reasoning and discussion	By requesting information By observation against expectation An agent's tone of voice Team reasoning and discussion

Table 5.46: CG identification mechanisms used by specific agent groups

5.6.2. Mechanisms for repair of CG loss

Identifier	Mechanism
R1	Repeating the correct plan (when confirmation is requested) usually restores CG, especially at the "milestones" of the plan.
R2	Unsolicited repeating of a plan can restore CG, without knowing if the other agent has achieved the same CG or not. (safeguard)
R3	Explicit declaration of a dynamic state (position) can restore CG.
R4	Active request to ask for information you do not know or are not sure of; analysis and reasoning of their own (lack of) knowledge and seeking to correct it.
R5	Explicitly stating what not to do when changing a plan or course of action can restore CG if it has been lost undetected.
R6	CG loss can be repaired by audio or visual observation as well, both in expected and unexpected scenarios.

Table 5.47: Mechanisms for the repair of the loss of CG

Following from before, some generalizations can be made in terms of the CG loss repair mechanisms used by the controllers as opposed to the ones used by the crews. The following Table 5.48 presents the same:

CREWS	CONTROLLERS
By confirmation of a plan By acknowledging an instruction By observation By explicit declaration of a dynamic state. By requesting repeat of some information (plan etc.)	By (solicited/unsolicited) repeat of a plan By requesting a state update By informing By observation

Table 5.48: CG repair mechanisms used by specific agent groups

5.6.3. Probable causes for the loss of CG

The loss of common ground can occur due to a very vast and unpredictable number of reasons ranging from inexperience to anger, exhibited by a human agent. It is not necessarily coordination mechanisms that cause the loss of CG among interacting agents. This is especially true because the external environment can also play a role in how the common ground among agents evolves. The breakdowns of coordination or CG losses identified in this study have been demonstrated in the final matrix, using the framework provided by Orasanu et al. [1] and have been mentioned below:

1. Language - misunderstanding the intent of others, using non-standard terminology, saying one thing and meaning something else.
2. Individual differences - different comfort levels, personality, unprofessional behaviour.
3. Environment and technology
4. Human memory
5. Attention
6. (Incorrect) expectations.

5.7. Modelling in LEADSTO

Formalization of human interaction, reasoning and cognition not only enables a better understanding of coordination within humans but also provides an opportunity to better enable human-machine interaction in sociotechnical systems. For the purpose of this study, the LEADSTO/TTL language has been used for the formalization and mathematical modelling. Next, the LEADSTO software environment has been used for simulation purposes. State elements of the agents evolve over time and this is the dynamics that is needed to be modelled. The software describes the relationship between states by mathematical or logical means, or a combination thereof [3].

The "state" is characterized on the basis of ontologies that define a set of properties that may or may not hold at a certain time t. All the atomic state properties based on the ontology *Ont* are denoted by *APROP(Ont)*. Hence, the state properties can be formalized by the propositions made from the atomic state properties [3]. A state *S* indicates which state property is true and which false: S: APROP(Ont) → [true, false]. LEADSTO makes use of a temporal language that enables one to model direct temporal dependencies between two state properties in successive states (known as dynamic properties) [3]. The format has been defined as follows:

Let α and β be state properties and e, f, g, h are non-negative real numbers. The notation used in LEADSTO is: $\alpha \twoheadrightarrow_{e,f,g,h} \beta$ This means that if a state property α holds true for a certain time interval with a duration of g, then after some delay (between e and f) the state property β will hold true for a certain time interval of h duration.

Using this format, LEADSTO specifications can be written for each time point in the present accident study. These specifications can be easily derived from the formalization obtained by implementing the MASA framework [2], using the identified state elements of agents as transitions between states. For example;

$$f^{r}_{ATCO}(\text{plan(P5), position(on runway)})$$
$$\rightarrow$$
$$\sigma^{ATCO}_{t11,KLM-CREW}$$
$$= f^{mi}_{KLM-CREW,ATCO}(\text{ack position report})$$
$$= \text{knows(KLM-CREW, position(on runway))}$$

These are the set of equations obtained using the MASA framework to depict ATCo's acknowledgement to KLM-CREW's position report. The LEADSTO specifications for the same would be;

has_plans(ATCO, ATCO, P5) **&** *comm_to_from(ATCO, KLM_CREW, position(on_runway))* $\twoheadrightarrow_{0,1,1,1}$ *comm_from_to(ATCO, KLM_CREW, ack_position_report)*

comm_to_from(KLM_CREW, ATCO, ack_position_report) $\twoheadrightarrow_{0,1,1,1}$ *awareness(KLM_CREW, ATCO, knows(position(on_runway)))*

The following chapter presents a few more examples of specifications which were formulated. Although the case study presented has been analysed over 50 time points, it is important to note that in the LEADSTO environment, the simulation spans over around 250 time points which is closer to the real case. In physical reality, the official transcript lasts about 8 minutes or around 480 time points. This is because of certain approximations made during the analysis, these have been listed below:

1. Every communication output last one time step and the receiving agent observes the input communication in the subsequent one time step. This reduces the average time of a two-way communication to only about 3 - 4 time points. While in reality, this time would range from 3 - 15 time points or even higher.
2. The 1 minute long (60 time steps) of PA engineer's taxi check has not been considered for analysis because it is irrelevant to this case study.
3. Every internal crew communication has been considered as one single time step, only if needed since the crews act as a single agent.

5.8. Simulation in LEADSTO

Once the LEADSTO specifications have been modelled for all temporal dependencies between agents, the simulations are executed. The software produces a graphical output in the form of simple temporal traces. All these specifications are based on the $\alpha \twoheadrightarrow_{e,f,g,h} \beta$ format but can have internal versatility depending on the state properties and also, human reasoning. For example, there exist conditional and unconditional persistent types of LEADSTO specifications. Unconditional persistence means that α and β are the same state property (X) and

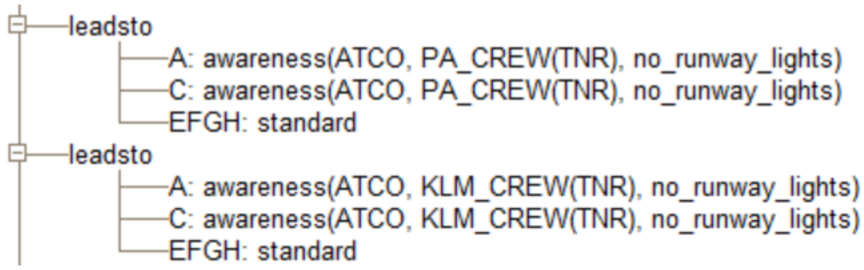

Figure 5.1: LEADSTO specification: unconditional persistence

if X is true then X is true. This is an infinite property that once true, will always be true.

In Figure 5.1, two unconditional persistence properties are depicted. The first one states that if agent ATCO is aware that PA-CREW is aware of 'no runway lights' at TNR for 1 time point, ATCO will have this awareness at the next time point, and so on. Similarly, there also exists a specification for KLM-CREW. Such persistence properties are rarely used because there are usually conditions that are capable of halting this persistence. Now, if there exists a condition (Y) that is true, then X will stop being true. Such a case would account for a conditional persistence.

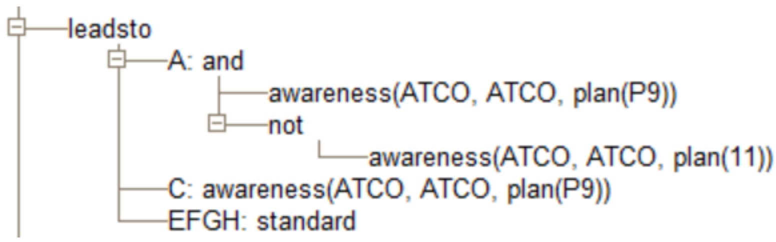

Figure 5.2: LEADSTO specification: conditional persistence

Figure 5.2 shows conditional persistence where the "awareness(ATCO, ATCO, plan(P11))" is the condition. This property says that ATCO will be self-aware of plan(P9) persistently until he is subsequently aware of plan(P11). Additionally, it is also possible for α or β to have multiple state properties within, conditioned together. This means that state properties A, B, C must be true for state properties M and N to be true, or any combination thereof. An example of such a specification is:

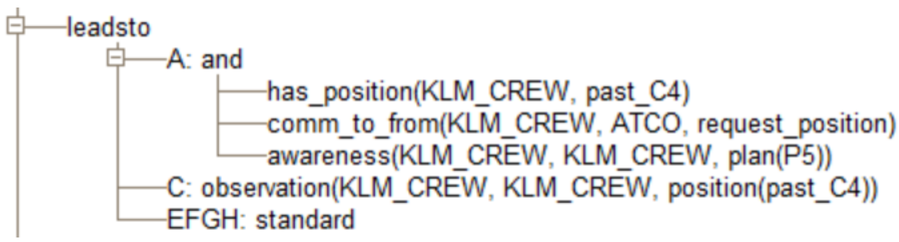

Figure 5.3: LEADSTO specification: multiple state properties that must be true for a certain consequence(s)

Figure 5.3 shows that three properties need to be true for a certain subsequence to occur. Here, KLM-CREW must actually have the position(past C4), have the request to report their position and also be aware of the plan(P5) that they are currently following to be able to make the observation of being at position(past C4), to then report it to ATCo.

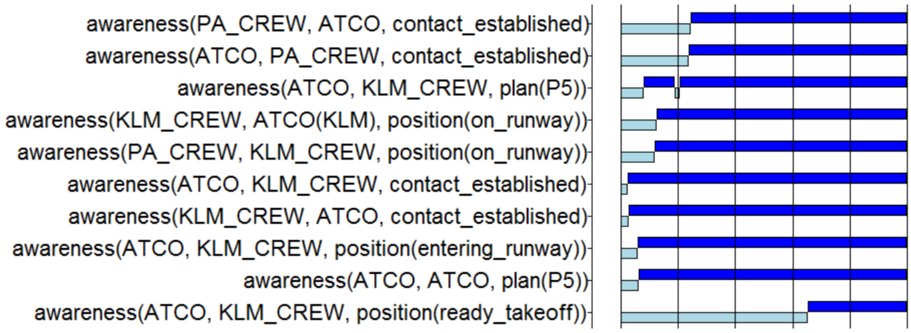

Figure 5.4: A (partial) snapshot of the temporal traces from the final simulation

Figure 5.4 is a partial snapshot from the final simulation of the accident case and depicts a very small fraction of the final temporal traces produced. This part of the traces show certain awarenesses that the agents exhibit. The dark blue traces mean that the state property holds true in the respective time points and the light-blue trace states that it is not true. In this snapshot, only the awarenesses that stay persistent through the entire time once they begin, have been shown. For example, both the KLM and PA crews are aware that they have established contact with ATCo and vice versa. This awareness does not change during the simulation because no such event (that breaks established contact) occurs in this case. Hence, it seems to be presented as unconditional persistence, which it is clearly not in reality. This is really a case of conditional persistence where the agent's awareness of "contact established" becomes false when, for example, the ATCo stops to respond to the crew's output communications. In case of awareness(ATCO, KLM_CREW, plan(P5)), the state property hold true for some time before it stops and starts again. In simple terms, this depicts that agent ATCO was aware that KLM-CREW knows plan(P5) but then the agent realises (due to some reason) that KLM-CREW does not know plan(P5) but soon enough this awareness is re-established (probably because of intentional action). The last trace shows the awareness of ATCo regarding KLM-CREW about their position(ready takeoff) and it begins to be true towards the end of the simulation. This awareness is also not correct because the KLM-CREW was already taking off as opposed to being ready for takeoff (undetected coordination breakdown/loss of CG). In this scenario, however, it is a persistent property because of KLM-CREW's ambiguous use of terminology and misinterpretation.

5.8.1. Face value validation

Once we have a working model of the case and specific identified mechanisms, we can use these mechanisms to see how they effect the coordination of the system. The model can be used to see how these mechanisms enable common ground, detect loss of CG and even repair the loss of CG. From the many identified mechanisms, some can be directly used to see if they have any effect on the known breakdowns of coordination and loses of CG. Such an exercise can help in visualising and validating the hypothesis that certain CG loss could be identified or repaired. In addition to this, it will help in understanding how a mechanism would detect or repair a loss of CG. Subsequently, this exercise could also reveal unprecedented information pertaining to how certain coordination mechanisms will effect a certain ATM scenario. Selected mechanisms from the identified coordination mechanisms in Section 5.6 have been implemented in the final model of the accident case and the following table demonstrates the obtained results and information. The first column explains the mechanism used, the second column specifies the agent which incorporates the particular mechanism in their coordinative activities. The third column presents what is the effect on any or all agents pertaining to the identification of a certain loss of CG. The final column demonstrates the effect of the mechanism used on any or all agents pertaining to repairing the loss of CG.

While most mechanisms are simplistic, like repeating a message or confirming a plan, they are most useful and realistic. This is because of how humans communicate and form beliefs. It is quite usual for a human agent to hear an instruction more than once to really grasp it just because of momentary distraction or cultural/lingual differences. Therefore, mechanisms like repeating, confirming, informing, requesting to repeat etc. are extremely basic and necessary. It is also important to note that the presence and/or usage of these mechanisms will not always lead to what is expected. The possibility of it not working or producing another unexpected result also definitely exists. An over-usage or over-reliance on these mechanisms will also most certainly have an opposite-to-intended affect. This is why it is important to make the distinction between looking at these mechanisms as an "**an aid**" in enabling human-human & human-machine coordination in complex systems, instead of looking at them as any kind of **solution**.

Mechanism used	**Used by Agent**	**Identified CG losses**	**Repaired CG losses**
D7	KLM-CREW	Repeated instruction to standby for takeoff leads to KLM-CREW realizing that they have been asked to standby for takeoff.	KLM-CREW does not initiate takeoff unless they explicitly receive takeoff clearance afterwards, impact is most probably avoided.
D3	KLM-CREW	KLM-CREW is aware that PA-CREW is still on the runway, unsure which exit to take. This is because of regular CG update regarding PA aircraft's position.	KLM-CREW does not initiate takeoff as they don't wrongly assume that PA-CREW is off the runway.

Table 5.49: Implementation of mechanisms, page 1

Mechanism used	Used by Agent	Identified CG losses	Repaired CG losses
R3	PA-CREW	KLM-CREW hears that PA-CREW is on the runway and has an active awareness of this state and does not make a wrong assump--tion regarding the location of the KLM aircraft.	KLM-CREW does not initiate takeoff as they are aware that PA-CREW is on the runway, possibly even if they interpreted ATC clearance as takeoff clearance; impact is probably avoided.
D9	PA-CREW	PA-CREW recognise that they are not completely aware of the infrastruc--ture of the TNR airport and inform ATCO of the same.	PA-CREW receives helpful information from ATCO and does not get confused with C3 and C4 exits, impact might be avoided.
R5	ATCO	KLM-CREW receives the instruction for plan(P5) and also instruction to NOT follow plan(P3) or plan(P4).	KLM-CREW might not form plan(P4) due to mishearing or misinterpretation if it is stated what NOT to do. However, KLM-CREW could form a completely new plan due to mishearing.
D6	ATCO	KLM-CREW would probably be asked to standby for takeoff again as it is an impor--tant instruction.	KLM-CREW does not initiate takeoff unless they explicitly receive takeoff clearance afterwards, impact is most probably avoided.
D7	ATCo	KLM-CREW is asked to NOT takeoff unless cleared for it, after they inform that they are "ready for takeoff" or "at takeoff".	KLM-CREW does not initiate takeoff as they were asked NOT to, impact is probably avoided.

Table 5.50: Implementation of mechanisms, page 2

From this exercise, we not only see that many identifications and repairs of CG losses are surely possible, as anticipated, but also that it is a probabilistic scenario. This is to say that just because a mechanism works once does not mean it will always work with all human agents in all situations. Furthermore, just because the usage of a mechanisms prevents collision does not imply that it is *working*. This is so because in the real world, agents make use of many coordination mechanisms that work most of the times and not always. Hence, a cautious interpretation of the results is encouraged. There always exists a possibility that the common ground loss might occur on a much higher level, for example; a pilot not intending on safe operations. No matter how clear and accurate the communication between the pilot and the controller, a dangerous-minded pilot cannot be efficiently instructed. Some important takeaways from this exercise have been enlisted below.

1. It does not matter which agent uses a certain mechanism, many-a-times the other agents are also led to identification and repair of CG loss.
2. It is also seen that the **implementation of only one** of the mechanisms to one of the agents can probably avoid the impact due to an effect of multiagent interactions.
3. Simplistic mechanisms like **repeating of information** or an **explicit declaration** about a state work very well with almost all coordination processes and can aid in restoring CG pertaining to the most prevalent states of agents.
4. Awareness regarding an agent's own lack of knowledge (SA) might not be very useful unless **another agent is informed of this lack in CG** and is then actively repaired.
5. In certain high-risk situations, it would be helpful to tell an agent **what NOT to do** along with what to do. This could potentially life-saving in day-to-day hazardous situations.
6. The "human element" contained within the complex systems is capable of recognising, in self and the other agents, characteristics like doubt, tone of voice, hesitation or maliciousness. This **capability must be acknowledged and utilized**.

5.9. Variations of the case

After the mechanisms have been implemented and tested, performing a basic analysis of some variations of the scenario and how the coordination mechanisms affects this can further validate and lead to a better yet understanding of these coordination mechanisms. We have already learnt that the all the mechanisms have the potential to work and repair loss of CG, in more than one ways. However, the question still remains weather these mechanisms would hold up in a different scenario from the one studied in this case. Hence, the first step is to test the mechanisms in certain variations of the original case. A few key mechanisms have now been selected and implemented in the final model of the accident case. By introducing certain fundamental variations in the original scenario, it can be seen how the mechanisms would effect the operations within this sociotechnical system. The following mechanisms are applied to the final model:

- Request repeat of information in case of disturbance, illegible audio, mishearing etc. (D7) - applies for all agents.

- Explicit declaration of one's dynamic state, specially when it changes, so as to make aware the other agents. (R3) - applies for both crews.

- Request repeat of message when wrong or unclear terminology is used. (D7) - applies for all agents.

- Repeating crucial parts of the plan, unsolicited. (D6) - applies only to ATCo.

The identified coordination mechanism **D7** is seen to be applied twice during these exercises. This is because this mechanism dictates the request to repeat information in case of a large number of events ranging from illegible audio to hearing incorrect terminology and hence, has a wide-spread application. These mechanisms will be validated by testing them on two simple variations of the original case. The first variation alters the visibility conditions. In the original scenario, the runway visibility conditions deteriorated from 2 - 3 km to 300 m in about 10 mins. This happens as the KLM aircraft began taxiing down the runway. The alteration is such that the visibility conditions only deteriorate 50% of the times and the visibility conditions remain high the other times. The abundance of visual data should repair many CG losses among agents during these times. The second variation introduces a ground radar equipment to aid the ATCo in his operations. In this case, with the help of the ground radar, it is assumed that the ATCo will notice when the PA aircraft fails to exit on the instructed C3 taxiway. This will mostly cause the controller to communicate with the PA-CREW and help them with the taxi instructions as their lack of awareness of TNR will be evident. As the KLM-CREW do not pay a close attention to the communication between the PA-CREW and ATCo until the very end, it is plausible that they might initiate takeoff just as in the original scenario. When the ATCo notices the KLM aircraft performing a takeoff roll (in the ground radar), it is very unlikely that he can do anything to stop the aircraft at that time or to avoid the collision. This variation is intriguing because the ground radar is a standard equipment used around the world at all airports today. Tenerife airport did not have it in 1977 and it would be interesting to see if its presence could have had a significant effect in terms of the mechanisms used.

5.9.1. Face value validation

In line with the hypothesis that the mechanisms will work in a variable scenario, all the applied mechanisms work well in both the variations. In the first variation, there is an uncertainty regarding their usefulness when the visibility conditions do not deteriorate. Similarly, in the second variation the mechanisms continue to play a very important role and lead to some interesting and some unexpected findings. Finally, as expected, it is also seen that the usage of these mechanisms in both the variations of the scenario do not lead to any new evident negative effect on the coordination (not focusing on the coordination costs pertaining to time and effort of the agents). This is probably because the implemented mechanisms are basic to human interactions and are extensively used in almost all sociotechnical settings.

Variation 1: Visibility conditions do not deteriorate
This variability analysis shows how the mechanisms will have different effects (if any) in the original scenario as compared to a scenario where the visibility does not deteriorate at all. During high runway visibility, visual observations can be made which provide a higher degree of certainty regarding the information obtained when compared to audio communications. The following things were learnt:

1. When the visibility does not deteriorate, the two aircraft can see each other and hence the KLM-CREW does not initiate takeoff, no matter what the misinterpretation. Visual observation has the most significant effect and plays a very major role in repairing loss of CG. This can be seen towards the end in the original case when the two aircraft have a visual of each other, 8 seconds before impact, and take immediate actions to avoid the disaster.

2. When the visibility conditions are good, the ATCo can also see the two aircraft on the runway and has an accurate CG regarding their position states. In this case, many communications pertaining to position states become redundant. The ATCo can easily direct the aircraft if he can see them in real time in front of him (mainly because TNR is a small single runway airport). ATCo might also realise PA-CREW's lack of awareness regarding airport infrastructure and take corrective steps.

3. It is plausible to say that despite the loss of CG because of miscommunication, wrong terminology, stress, illegible audio or misinterpretation etc., the collision probably wouldn't have occurred if the visibility conditions were good. This goes on to show that only by altering a small detail in the scenario, we notice that all the previously significant "human errors" are now no more than just normal human-behaviour on another day at work.

Variation 2: ATCo has a ground radar equipment
This variability analysis focuses on a case where the ATCo has information about the crews' position states at all times on the ground radar which is available to him. The applied mechanisms work well in this case as well. While ATCo has a visual aid when the visibility is low, the crews still have less than 500m of visibility. Hence, this scenario depends on a heavy reliance on ATCo and his communications. The following things were learnt:

1. As the PA aircraft misses the C3 exit, the ATCo notices this and communicates with the crew and directs them to the next exit. The ATCo is now aware of PA-CREW's confusion. The PA-CREW is also aware of their lack of knowledge of TNR. It is possible that the ATCo might inform KLM-CREW of this changed situation and ask them to wait longer. However, it is also possible that the KLM-CREW takes off as the ATCo is communicating with PA-CREW without waiting for clearance (as in the original case).

2. The ATCo might also notice as the KLM aircraft begins its takeoff roll after only receiving ATC clearance. As soon as ATCo realizes this and communicates it to the KLM-CREW, it might not be soon enough for the KLM 747 to go off the runway to avoid impact.

3. It is also learnt that the presence of the ground radar did not necessarily avoid the impact from occurring. The mechanisms, on the other hand, do play a major role.

4. The presence of ground radar means that the ATCo does not have to rely on the aircraft crews to obtain their current position on the ground. This means that he can update his CG regarding the position states of the aircraft crews timely and form further plans to guide them. It is plausible that this would reduce the level of stress on the ATCo at Tenerife who was not used to managing jumbo jets on that small airport. Therefore, while it is possible that the presence of a ground radar might not directly have avoided the collision, it is also plausible that its presence might have reduced ATCo's stress and raised his efficiency which could have played a part in avoiding the accident that day.

6

Conclusions and Recommendations

After modelling the coordination, theoretically and agent-based), identifying mechanisms revolving around CG loss and its repair, checking their usefulness and validity via simulations, this chapter presents the lessons learnt. The foremost understanding pertains to the complexity of coordination in sociotechnical systems and the need to acknowledge such a system's *emergent nature*. This further implies that such a system will usually have some degree of *uncertainty, temporal dependencies with a probabilistic nature in reality, unavoidable external disturbances, multiple distributed interactions among diverse actors and an unpredictable quality*. As the human factor is largely involved, this makes the system a high-stake one and the need to be operationally safe and efficient is also high. For this, the system should not only be able to overcome external hurdles but also learn from them and adapt for the future. Such a system cannot be and must not be optimized but it must be well-enabled, efficient and resilient. The human-human and the human-machine interaction can be enabled by better understanding the human factor and how it can complement the machine and mainly, how the machine can enable the human instead of replacing the human. Some general conclusive remarks pertaining to coordination mechanisms and common ground in coordination have been enlisted:

- It is seen that the common ground between agents is **lost undetected multiple times**, even pertaining to very crucial states, **but is also recovered soon enough**. These losses are usually not detected and are repaired because of coordination mechanisms that are being used by the agents. These coordination mechanisms range from basic communication etiquettes to protocol-based actions.

- Following from the previous remark, it is also noted that a **loss in common ground need not be identified for it to be repaired**. Often the coordination mechanisms used as safeguard (like unsolicited repeat of a crucial instruction) repair the CG loss even without ever identifying it.

- While established aviation protocols take care of the most common (and predictable) CG losses during coordination, it is the unforeseen coordination breakdowns that the system must fix and overcome. An automated system witnesses its limits if any given situation deviates from predefined parameters. Hence, **for a complex high-risk system, only an intelligent, resourceful and capable agent should be in control**. This is not to say that automation is not effective, but only to realise the importance of the human factor. A system that enables the interaction between the human and the machine with the two enabling each other as well.

- Although many coordination mechanisms have been identified with various functionalities, **none of them can be a hundred percent reliable** to overcome even only one kind of CG loss at any or all time points in the future, for any or all agents. This is because of the basic unpredictability of sociotechnical systems, which by definition are undefined. Even though a 100% reliability cannot be guaranteed, **a better understanding of coordination can lead to a high, or even a very-high, reliability**. In an undefined and unpredictable sociotechnical system, just as in life, we try to go for the best odds because a 100% reliability is unrealistic.

- When an agent starts to lose common ground with respect to a particular state and is aware of this loss, the loss is actively repaired by that agent. Most **coordination breakdowns occur when the agent is completely unaware of this loss and does not realise this unless the breakdown presents itself** in the physical world (like an alert or an angry email from your boss).

- Following from the previous remark, the agents usually lose common ground regarding the states of other agents by **wrongly assuming the other agent's intents or beliefs**, leading to incorrect expectations. This is when an agent expects another agent to do something at sometime in the future and also assumes that the other agent is aware of this obligation. However, when this action is not done, the breakdown of coordination highlights the loss of CG.

- The memory plays a very important role in any and all human coordination. As humans are known to not have the best or the most reliable memories, many coordination breakdowns occur when humans simply forget a small step. With all things being perfect, the **human memory can still fail us**. With simple inputs like stress or distraction, the human agent can tend to be forgetful.

- It is possible that two agents have a lower-level common ground regarding a certain state, like a plan they must follow together, and yet due to a lack of a higher-order understanding a coordination breakdown occurs. This is if the agents know the same plan but **interpret it differently without even realising that their interpretations are different**, namely a difference in stance.

Conclusions - ATM case study

When considering the specific accident case studied in this master thesis, a separate set of specific conclusions and lessons can be drawn. While there exists no single "reason" why the accident occurred and the aim of this research was not to find such causal relations, it is useful to note that the identification and elimination of such causes is in line with the traditions Safety-I approach and is not enough. To be in line with the modern Safety-II view, we must focus on the coordination processes themselves and try to understand them better. Hence, the following conclusive remarks have been made:

- This accident case exemplifies a scenario where a large amount of job experience along with perfect CG among team members regarding the goal led to a disaster due to an agent's level of stress and authoritative nature combined with bad visibility conditions. All such things are **a sequence of normal occurrences which, in this case, randomly turned deadly**. This is an important characteristic of any sociotechnical system and must be accepted and understood to better enable it for resilient operations.
- With the help of simulations it is seen that even if only one agent incorporates a coordination mechanism that corrects a crucial CG loss, **this repair of CG affects all the agents due to effect of multi-agent interactions** in a dynamical sociotechnical system.
- The basic coordination mechanisms used in everyday interactions like repeating important parts of the plan, requesting repeat of information in case of mishearing or illegible audio etc. are the most important mechanisms when it comes to identification of CG loss and repairing it. The **fundamental nature and redundancy of these mechanisms should not be undermined** as these mechanisms are the very basis of coordination.
- There are always crucial states regarding which agents must, at all times, maintain common ground. These crucial states have been identified in section 5.6. If agents **know what these crucial states are and know that they must maintain CG with other agents regarding these states**, then the agents will be better enabled to operate in their surroundings and better advised to take machine help.
- Currently, autopilots are trusted to do the simplest tasks like cruise control while the pilot has to ability to takeover if the situations turns away from standard. While this is understandable, it is also questionable if this is the best way to handle the situation. This is because while the human can be more creative, intuitive or motivated than a machine, the human can also be fatigued, scared or delusional, unlike a machine. Hence, the **human and the machine together have the best chance of overcoming a tricky situation** instead of individually.
- There are, of course, certain aspects that if different might have not led to the collision, for example; if the KLM aircraft had not fully refuelled then they would have probably lifted off over the PA aircraft, if the visibility conditions were good then the KLM captain would not have initiated takeoff, if the KLM captain was not stressed then he might not have forgotten the takeoff clearance and the list is endless. Hence, it is **not fruitful to try and**

find a reason(s) but to analyse the process of coordination as a whole.

- Once the context is changed, the previously significant "human errors" of the case are suddenly reduced to only normal human-behaviour and interaction. This shows that **there are no errors but just partially understood human interaction**. This is important to note because understanding the technicality is as vital as understanding the way in which to view the "human factor".

Recommendations - ATM safety

Based on the findings of the analysis of the accident study and the conclusive understandings, some recommendations can be made in the direction of how agents can sustain, update, monitor and repair common ground in a complex sociotechnical system to make it more resilient. These recommendations are predominantly aimed at the **air traffic and management** sector with the purpose to contributing towards the **safety of aviation**. The following recommendations revolve *around enriching the human-machine interaction, changing the way one views the human-factor in a system and the ways of sustaining common ground* in a system:

1. Agents should be made aware of what are the crucial states regarding which CG must be maintained at all times. This could provide a clearer context and the inclination to work towards this incentive itself. In operation, as an agent's position is very important in the aviation operations, it could be mandatory for all the agents to always **explicitly declare** any change in their dynamic state, even when on the ground at the airport.
2. In the event of a certain change of plans or in a crucial situation, it is advisable that the agents are instructed **what <u>not</u> to do** along with what should be done. This recommendation focuses on ensuring what not to do but can prove to be dangerous if interpreted as the opposite instruction. Hence, clear communication is key here. For example, if the KLM-CREW was explicitly told to not takeoff because of PA 747's position, it is plausible that they would not have made the opposite assumption.
3. It is crucial that agents or teams have common ground on multiple levels and have the ability and inclination to **engage in a discussion to realise one's own lack of knowledge**. As mentioned earlier, two agents might be following the same plan with complete different interpretations without having any awareness or expectation of their interpretations being different. It is also possible that an agent has insufficient awareness about a certain aspect but is unaware of this fact. It is quite difficult to realise that what one does not know but must know. Hence, it is good to realise such a lack and seek to correct it.
4. Modern aircraft use many kinds of on-flight computers that aid the pilots in numerous tasks and in providing much needed physical world data. Modern aircraft also have highly advanced autopilots fully capable of flying any aircraft. With another integrative step, we can implement a "**smart agent**" that not only provides the relevant information but keeps track of what the aircraft crew are doing. Having a subtle smart assistant can help the human

in many ways such as;

- When the *protocol is not being followed* (intentionally or unintentionally), the smart agent should make the entire crew aware of this.
- The smart agent could also *timely remind* the human agents of crucial state properties of self/other agents regarding which CG must be maintained at all times. This is so as the CG is updated.
- Because humans exhibit bad memory traits, the smart agent can pick up the slack. When the human is forgetting some step, the smart agent can *ensure the human remembers* all it needs to remember for safe operations.
- The smart agent can also have a threshold time pertaining to certain state properties and should *remind the crew of the "outdated" information* with the need to update it.

Future work

As this field of ATM safety is relatively young, there is a lot that is to be researched and understood. Apart from the obvious challenges that we encounter when dealing with physiological science and its inscrutable nature, there are still quite a few challenges that will have to be overcome in the coming years.

1. It is not only important to study ATM safety with the updated Safety-II view but also approach the complex ATM systems as sociotechnical systems.

2. It seems increasingly important to incorporate psychological and social science at the very basis of STS when studying coordination or modelling coordination.

3. Comparative studies between models of coordination of an ATM hazard vs. an ATM regular operation would also provide interesting insights regarding the underlying coordination mechanisms.

4. The traditional view that higher optimization leads to higher efficiency is, if not flawed, incomplete and has to be adapted for sociotechnical systems and their coordination processes.

5. Defining safety by the absence of accidents is almost like grading a student by the information he did not understand. This is a weakness which must be accepted and corrected.

While it is true that the costs of coordination can be seen in terms of the usage of extra time, effort etc., what value can be given to safety? It is definitely important to find a harmonious balance but this balance cannot be decided before the human factor is barely even understood. Until then, safety is just philosophy which is attempted to be explained by the lack of some unsafe events. As always, to understand safety scientifically, we must understand how we perform successful actions everyday and explain "safety" with the relevant evidence.

A

Appendix

A.1. Identified goals, plans, activities, expectations, events and stances

Goals

TERM	AGENT	Description
G1	KLM-CREW	Takeoff ASAP
G2	KLM-CREW	Safe and efficient operations
G3	ATCo	Safe and efficient operations
G4	PA-CREW	Takeoff after KLM
G5	PA-CREW	Safe and efficient operations

Plans

P1	KLM-CREW	Backtrack following aviation protocol
P2	ATCo	Guide KLM aircraft following aviation protocol
P3	ATCo	Grant KLM taxi clearance and provide KLM with taxi instructions to begin backtrack and exit at C3 exit, following aviation protocol.
P4	KLM-CREW	KLM-CREW's interpretation of plan P3 with the instruction to exit at C1 instead of C3, following aviation protocol.
P5	ATCo	A new plan for KLM taxi to achieve the same goal. Plan is to backtrack all the way end of runway 30, following aviation protocol.
P6	PA-CREW	Contact ATCo and backtrack (=taxi down the runway) following aviation protocol.
P7	ATCo	Guide PA aircraft following aviation protocol.
P8	ATCo	Grant PA taxi clearance and provide PA with taxi instructions to begin backtrack and exit at C3 exit, following aviation protocol.
P9	ATCo	KLM to turn 180 at the runway end and report when they're ready for ATC clearance, following aviation protocol.
P10	ATCo	Inform the crews of non-availability of centre-line marking on the runway.
P11	ATCo	Grant ATC clearance to KLM and instructions for KLM after takeoff.
P12	ATCo	KLM should standby for takeoff.
P13	KLM-C	Turn 180 at runway end and takeoff.
P14	KLM-CREW	KLM-CREW's interpretation of plan P11.

Activities

A1	KLM-CREW to ATCo	"Approach KLM 4805 on the ground in Tenerife."
A2	ATCo to KLM-CREW	"KLM -ah- 4805, roger."
A3	KLM-CREW to ATCo	"We require backtrack on 12 for takeoff runway 30."
A4	ATCo to KLM-CREW	"Okay, 4805...taxi...to holding position runway 30. Taxi onto the runway and -ah- leave runway (third) to your left."
A5	KLM-CREW	KLM begins taxiing down the runway.
A6	KLM-CREW to ATCo	"Roger, sir (entering) the runway at this time and the first (taxiway) we, we go off the runway again for the beginning of runway 30."
A7	ATCo to KLM-CREW	"Okay, KLM 80 -ah- correction, 4805, taxi straight ahead -ah- for the runway and -ah- make -ah- backtrack."
A8	KLM-CREW to ATCo	"Roger, make a backtrack."
A9	KLM-CREW	KLM is now on the runway.
A10	KLM-CREW to ATCo	"KLM 4805 is now on the runway."
A11	ATCo to KLM-CREW	"4805, Roger."
A12	KLM-CREW to ATCo	"Approach, you want us to turn left at Charlie 1, taxiway Charlie 1?"
A13	ATCo to KLM-CREW	"Negative, negative, taxi straight ahead -ah- up to the end of the runway and make backtrack."
A14	KLM-CREW to ATCo	"Okay, sir."
A15	PA-CREW to ATCo	"Tenerife, the Clipper 1736."
A16	ATCo to PA-CREW	"Clipper 1736, Tenerife."
A17	PA-CREW to ATCo	"Ah - we were instructed to contact you and also to taxi down the runway, is that correct?"
A18	ATCo to PA-CREW	"Affirmative, taxi into the runway and – ah – leave the runway third, third to your left."
A19	PA-CREW	Begins taxi down the runway, following KLM aircraft.
A20	PA-CREW to ATCo	"Third to the left, okay."
A21	ATCo to PA-CREW	"[Th]ird one to your left."
A22	PA-CREW to PA-CREW (internal)	"I don't think they have takeoff minimums anywhere right now."
A23	ATCo to KLM-CREW	"KLM 4805, how many taxiway – ah – did you pass?"
A24	KLM-CREW to ATCo	"I think we just passed Charlie 4 now."
A25	ATCo to KLM-CREW	"Okay... at the end of the runway make 180 [degree turn] and report – ah – ready – ah – for ATC clearance."
A26	PA-CREW to ATCo	"– Would you confirm that you want Clipper 1736 to turn left at the THIRD intersection?"
A27	ATCo to PA-CREW	"The third one, sir, one, two, three, third, third one."
A28	PA-CREW to ATCo	"Very good, thank you."
A29	ATCo to PA-CREW	"...er 7136 [sic] report leaving the runway."
A30	ATCo to [KLM-CREW & PA-CREW]	"[KLM] 8705 [sic] and Clipper 1736, for your information, the centerline lighting is out of service."
A31	KLM-CREW to ATCo	"I copied that."
A32	PA-CREW to ATCo	"Clipper 1736."
A33	KLM-CREW	KLM aircraft turns 180 degress at the end of the runway.
A34	KLM-C	Initiates takeoff.
A35	KLM-F to KLM-C (internal)	"Wait a minute, we don't have ATC clearance."
A36	KLM-C to KLM-F (internal)	"No, I know that. Go ahead, ask."
A37	KLM-CREW to ATCo	"Uh, the KLM 4805 is now ready for takeoff and we're waiting for our ATC clearance."
A38	ATCo to KLM-CREW	"KLM 8705 [sic] uh you are cleared to the Papa beacon. Climb to and maintain flight level 90 ... right turn after takeoff proceed with heading 040 until intercepting the 325 radial from Las Palmas VOR."

A39	KLM-CREW to ATCo	"Ah, roger, sir, we're cleared to the Papa beacon flight level 90, right turn out 040 until intercepting the 325, and we're now (at takeoff)."
A40	KLM-CREW	KLM initiates takeoff, release brakes and accelerate.
A41	ATCo to KLM-CREW	"Okay."
A42	ATCo to KLM-CREW	"Stand by for takeoff ... I will call you."
A43	PA-CREW to ATCo	"And we are still taxiing down the runway, the Clipper 1736."
A44	ATCo to PA-CREW	"Ah—Papa Alpha 1736 report runway clear."
A45	PA-CREW to ATCo	"Okay, we'll report when we're clear."
A46	ATCo to PA-CREW	"Thank you."

Expectations

E1	KLM-CREW from ATCo	Expect acknowledgement of attempt to establish communication.
E2	ATCo from KLM-CREW	Expect further communication from KLM after acknowledging their attempt to establish communication.
E3	KLM-CREW from ATCo	Expect taxi clearance and taxi instructions.
E4	ATCo from KLM-CREW	Expect acknowledgement to taxi instructions.
E6	KLM-CREW from ATCo	Expect acknowledgement of reporting position.
E7	ATCo from KLM-CREW	Expects KLM to acknowledge new taxi instructions.
E10	KLM-CREW from ATCo	Expect to acknowledge their update of position communication.
E12	KLM-CREW from ATCo	Expect confirmation of taxi instructions.
E13	ATCo from KLM-CREW	Expect acknowledgement of correct taxi instructions.
E15	PA-CREW from ATCo	Expect acknowledgement of attempt to establish communication.
E16	ATCo from PA-CREW	Expect further communication from KLM after acknowledging their attempt to establish communication.
E17	PA-CREW from ATCo	Expect taxi clearance and taxi instructions.
E18	ATCo from PA-CREW	Expect acknowledgement for taxi instructions.
E23	ATCo from KLM-CREW	Expect KLM to report latest position.
E24	KLM-CREW from ATCo	Expect ATCo to respond to this report of position.
E25	ATCo from KLM-CREW	Expect KLM to report when they're ready for ATC clearance, after turning 180 at runway end.
E26	PA-CREW from ATCo	Expect ATCo to confirm taxi instructions.
E27	ATCo from PA-CREW	Expect PA to acknowledge repeat of taxi instructions.
E29	ATCo from PA-CREW	Expect PA-CREW to report when they are off the runway.
E30	ATCo from [KLM-CREW & PA-CREW]	Expect both the crews to ackowledge airport information.
E35	KLM-F from KLM-C (internal)	Expect KLM-C to stop takeoff initiation.
E36	KLM-C from KLM-CREW	Expect to request ATCo for ATC clearance.
E37	KLM-CREW from ATCo	Expect to receive ATC clearance from ATCo.
E38	ATCo from KLM-CREW	Expect KLM to acknowledge ATC clearance and instructions.
E39	KLM-CREW from ATCo	Expect ATCo to acknowledge this communication.
E40	KLM-CREW	Expect to takeoff safely.
E42	ATCo from KLM-CREW	Expect KLM to standby and wait for takeoff clearance.
E43	PA-CREW from ATCo	Expect ATCo to acknowledge PA's position on the runway.
E44	ATCo from PA-CREW	Expect PA to report when clear off the runway.
E45	PA-CREW	Expect no takeoffs until PA reports clear off runway.

Events

Ev1	TNR(all agents)	Visibility drop < 500m
Ev2	PA-CREW	Visual contact with KLM 8 seconds before impact.

Analysis

An1	ACTo	Listening to KLM-CREW's intent and plan and forming a plan to guide them.
An2	KLM-CREW	KLM-CREW hears ATCo's plan for them to taxi.
An3	ATCo	ATCo hears KLM-CREW acknowledging wrong taxi instructions.
An4	KLM-CREW	KLM-CREW hears and interprets the correct taxi instructions that is meant for them.
An5	PA-CREW	PA-CREW's hears ATCo's plan for them to taxi.
An6	PA-CREW	PA-CREW observes the low visibility conditions at the airport and develops a belief that there most probably won't be any take off minimums anywhere when
An7	ATCo	Listening to KLM-CREW's latest position and forming the next part of the plan to guide them.
An8	KLM-C	Listening to ATCo's plan P9 to interpret and form plan P13
An9	KLM-CREW	KLM hears plan P and updates it as plan P9.
An10	KLM-C	KLM Capt observes the takeoff interruption KLM First Officer and forms plan P9.
An11	ATCo	ATCo heard KLM's request for ATC clearance and forms the next part of the plan for KLM.
An12	KLM-CREW	KLM-CREW hears the ATC instructions and updates the previous plan.
An13	KLM-CREW	KLM crew hears PA tell ATCo that they are still on the runway and ATCo acknowledge this and ask PA to report when clear off the runway, after KLM is already take off rolling down the runway.

Stances

S1	KLM-CREW	Realize that PA is still on the runway.

A.2. Identified state elements

Discrete valued (mode) state elements

KLM-CREW	PA-CREW	ATCo
goal(G1)	goal(G4)	goal(G3)
goal(G2)	goal(G5)	plan(P2)
plan(P1)	plan(P6)	plan(P3)
plan(P4)		plan(P5)
event(visual contact with PA)	event(visual contact with KLM)	plan(P7)
		plan(P8)
		plan(P9)
		plan(P10)
requested taxi clearance	requested taxi clearance	plan(P11)
contact established	contact established	plan(P12)
received taxi clearance	received taxi clearance	contact established, KLM
received taxi instructions	received taxi instructions	granted taxi clearance, KLM
requested ATC clearance		contact established, PA
received ATC clearance		granted taxi clearance, PA
requested takeoff clearance		granted ATC clearance, KLM
received takeoff clearance		acknowledge contact, KLM
request contact	request contact	acknowledge contact, PA
stance(S1)	event(low runway visibility)	
stress due to Dutch duty limits		
		repeat taxi instructions, KLM
		repeat taxi instructions, PA
event(KLM impact PA)	event(KLM impact PA)	
report position	report position	

In the following table, t refers to the corresponding time-point in the transcript when a certain intention was generated by an agent. Similarly, x refers to the respective future time corresponding to the intention. Next, expectations Ew, Ex, Ey and Ez refer to the respective set of identified expectations of every agent. Times ta, tb, tc and td refer to the corresponding time-points in the transcript when the expectations are generated. p, q, r and s refer to the future time points until when the respective expectation will last.

Intent valued state elements

KLM-C	KLM-CREW	PA-CREW	ATCo
intent(liftoff over PA, t+x)	intent(reconfirm taxi instructions, t+x)	intent(reconfirm taxi instructions, t+x)	intent(KLM, request position, t+x)
		intent(report position, t+x)	intent(repeat instructions, t+x)
		intent(go off runway, t+x)	intent(provide runway light information, t+x)
expectation(Ew, ta+p)	expectation(Ex, tb+q)	expectation(Ey, tc+r)	expectation(Ez, td+s)

Bibliography

[1] C. Bearman, S. B. F. Paletz, J. Orasanu, and M. J. W. Thomas. The breakdown of coordinated decision making in distributed systems. *Human factors*, 52 (2):173–188, 2010.

[2] H. A. P. Blom and A. Sharpanskykh. Modelling situation awareness relations in a multiagent system. *Applied Intelligence*, 43(2):412–423, 2015.

[3] T. Bosse, C. M. Jonker, L. Van Der Meij, and J. Treur. LEADSTO: A language and environment for analysis of dynamics by simulaTiOn. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, pages 165–178, 2005.

[4] R. Chow, K. Christofferesen, D.D. Woods, and J. Watts-Perotti. Communication During Distributed Anomaly Response and Replanning. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 44(1):1–50, 2000.

[5] H.H. Clark and S.E. Brennan. Grounding in Communication. *Perspectives on Socially Shared Cognition*, pages 222–233, 1991.

[6] M.R. Endsley. Toward a theory of Situation Awareness in Dynamic Systems. *Human Factors*, 37(1):32–64, 1995.

[7] A. Espinosa, J. Lerch, and R. Kraut. Explicit vs. Implicit Coordination Mechanisms and Task Dependencies. *Statewide Agricultural Land Use Baseline 2015*, 1(January), 2015.

[8] Eurocontrol. A White Paper on Resilience Engineering for ATM. *Cooperative Network Design*, pages 1–16, 2009.

[9] P. Gerrans. Imitation and Theory of Mind. In *Handbook of Neuroscience for the Behavioral Sciences*, pages 905–922. John Wiley & Sons, Inc., 2009.

[10] G. Grote and E. Zala-Mezö. The effects of different forms of coordination in coping with work load : Cockpit versus operating theatre. (March), 2004.

[11] E. Hollnagel, J. Leonhardt, T. Licu, and S. Shorrock. From Safety-I to Safety-II: a white paper. *Brussels: European Organisation for the Safety of Air Navigation (EUROCONTROL)*, 2013.

[12] G. Klein, P.J. Feltovich, J.M. Bradshaw, and D.D. Woods. Common Ground and Coordination in Joint Activity. In *Organizational simulation*, chapter 6, pages 139–184. John Wiley & Sons, Inc., 2005.

[13] T.W. Malone and K. Crowston. What is coordination theory and how can it help design cooperative work systems? *Proceedings of the 1990 ACM conference on Computer-supported cooperative work*, (April):357–370, 1990.

[14] H. Mintzberg. The Structuring of Organizations: A Synthesis of the Research, 1979.

[15] P. Siebers and U. Aickelin. Introduction to Multi-Agent Simulation. *Ecology*, pages 1–25, 2010.

[16] S.H. Stroeve, B.A. van Doorn, and M.H.C. Everdij. Analysis of the roles of pilots and controllers in the resilience of air traffic management. *Safety Science*, 76:215–227, 2015.

[17] A. Vespignani. Modelling dynamical processes in complex socio-technical systems. *Nature Physics*, 8(1):32–39, 2011.