**Citation (APA)**
Kaur, M., & Sharpanskykh, A. (2026). Common Ground in coordination: The case of the 1977 Tenerife runway collision. *Cognitive Systems Research*, *99*, Article 101503. https://doi.org/10.1016/j.cogsys.2026.101503

Cognitive Systems Research 99 (2026) 101503

Contents lists available at ScienceDirect

Cognitive Systems Research

journal homepage: www.elsevier.com/locate/cogsys

# Common Ground in coordination: The case of the 1977 Tenerife runway collision

Mannat Kaur [a,*], Alexei Sharpanskykh [b]

[a] Internet Architecture Group, Max Planck Institute for Informatics, Saarbrücken, Germany
[b] Operations & Environment, Aerospace Engineering, TU Delft, the Netherlands

ARTICLE INFO

*Keywords:*
Coordination
Human factors
Agent-based modelling
Common ground
Aviation safety
Operations safety

ABSTRACT

Over a century has passed since humans took to commercial flying and the pursuit of safe operations continues today. The need to better understand the human factor as part of sociotechnical systems has become clear in recent times. In this paper, we focus on human coordination through a case study of a runway collision at Tenerife airport in 1977. We formalize coordination using theoretical frameworks and mathematically model it using agent-based techniques. For validation, we use LEADSTO simulations and perform a variability analysis. We identify coordination mechanisms that play an important role in identifying and repairing loss of common ground. Ultimately, we aim to add to the growing body of knowledge pertaining to the understanding of human cognition in complex sociotechnical systems in order to support resilient system operations.

## 1. Introduction

Air transport is an important and efficient way to travel for many people. This mode of transportation provides immense advantages when travelling large distances, particularly intercontinental. 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 which comprise of interacting social and technical agents 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 resilient.

Air traffic management (ATM) safety practices formed over the years are in accordance with the traditional safety perspective, known as Safety-I. Safety-I employs an approach to ensure that the number of adverse outcomes is below the acceptable risk limit (Hollnagel et al., 2015). This is achieved by either predicting everything that can possibly go wrong during the operations and eliminating the causal factors or putting safety barriers on them by finding the cause after the effect (failure) has occurred and ensuring that it does not reoccur. Hence, Safety-I is mainly a *reactive approach* focused on *failure avoidance*. The shortcoming of this view is that it focuses on the small percentage of events that are considered as failures but ignores a large number of events that happen successfully day-to-day.

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. *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* (Hollnagel et al., 2015). Understanding how things usually go well will help us ensure that they go well as much as possible, in turn reducing the things that go wrong. This approach is *pro-active* and focuses on *enabling success*.

In ATM, as in many other sociotechnical systems, processes and interactions take place between numerous agents. These agents can be human or non-human (technological). 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 often governed by organizational policies, procedures or protocol. STS exist because multiple agents come to work together with the aim of achieving certain goals. To achieve these goals, the agents are involved in numerous interdependencies. To manage these inderdependencies, coordination is required. 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?

Understanding of how coordination is done in real STS and ATM is important to better understand how success is created in every day operations and how things usually go well. 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 among the participating agents is well established and repaired in case of a

* Corresponding author.
*E-mail addresses:* mkaur@mpi-inf.mpg.de (M. Kaur), o.a.sharpanskykh@tudelft.nl (A. Sharpanskykh).

https://doi.org/10.1016/j.cogsys.2026.101503
Received 19 June 2024; Received in revised form 24 March 2026; Accepted 23 July 2026
Available online 1 August 2026
1389-0417/

breakdown. Agents can have a well-established common ground about certain aspects and might need to regularly update the common ground regarding other aspects. Thus, for effective coordination in STS, it is essential to establish and maintain common ground among the agents. The central research question addressed in this paper is

> *What mechanisms do agents use to sustain, update, identify losses of and repair common ground?*

To address this question, we performed a detailed formal modelling and analysis of an aviation case, which involves many coordination activities among several actors with detected and undetected losses of common ground, which eventually results in an accident. The methodology used in this study can be summarized in five steps:

1. Select framework(s) to create a formal model of coordination
2. Select an aviation case study
3. Use the selected frameworks to model the case
4. Detailed analysis of the model of coordination followed by identification of coordination mechanisms
5. Face value validation of the model

The main relevance of this study lies in the modelling of coordination using three theoretical frameworks which were integrated in a synergistic manner. This leads to a formalized representation of coordination patterns and mechanisms, with a specific focus on mechanisms that play a key role in identifying and repairing loss of common ground. The elements of common ground were systematically identified and formalized at three levels of awareness that are relevant not only for the case study considered in the paper, but also for the most ATM applications. In addition to retrospective analysis, the proposed modelling framework can also be used prospectively, in simulations of possible safety hazard scenarios and in real-time, real-life applications, for the timely identification and repair of losses in common ground. We elaborate on the contributions of our study in Section 6.

## 2. Theoretical foundation

The study of coordination mechanisms has only been around for a few decades. Although coordination is present everywhere in day-to-day life, it is challenging to analyse or formalize. This section provides background on coordination mechanisms as a theoretical basis for this project and discusses the requirements that motivate the choice of the theories to be used as the basis for our model. The three frameworks that were selected for modelling coordination are then presented.

### 2.1. Coordination in complex sociotechnical systems

Coordination can simply be understood as the act of working together in an organized way. Malone et al. define coordination as "*the act of managing interdependencies between activities performed to achieve a goal*" [Malone and Crowston (1990), p. 361]. Coordination can be a result: 'state of coordination' or it can be a process: 'coordinating'. 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 gets busier, the technology advances and the complexity of the systems keeps on increasing. Usually, more than one coordination mechanism is implicitly or explicitly used in real-world interactions. In complex, safety-critical STS, such as the air transport system, all three forms of coordination, described by Mintzberg (Mintzberg, 1989) - by mutual adjustment, by direct supervision and by standardization – play an important role. High-risk organizations highly standardize their operating procedures in order to reduce the 'human risk factor' (Grote et al., 2004). The rules and procedures are developed over time by observing failures and making safeguards. While these made sense in the past, it might not be enough for all types of complex systems, in which situations may occur for which no procedures exist. Furthermore, procedures and rules may not consider all possible contextual factors that exist in real life.

### 2.2. Desiderata for modelling coordination in complex safety-critical, sociotechnical systems

The main focus of our research is on understanding coordination in joint activities in complex STS, which is not limited to conversations or dialogues only, but also includes goal-setting, planning, and joint activity execution by the actors. The theory should not only consider coordination by communication (e.g., orally, in writing, formally, informally, interpersonally), but also be able to represent coordination by using task programming mechanisms (e.g., schedules, plans, procedures), which are essential in the work context of safety-critical organizations.

For actors to co-operate successfully, they must maintain models of each other as well as develop and maintain models of their future interactions. Actors may even achieve coordination without communication, provided they possess models of each other's behaviours. Using this knowledge, agents anticipate the actions and needs of the other agents and adjust their own behaviour and plans accordingly (Espinosa et al., 2004). In such a way they would be able to detect differences in situation awareness, which is an important risk factor in safety-critical STS. Implicit coordination is realised through group cognition, which is based on shared knowledge of the interacting actors about the task being executed, the environment, and about each other. Thus, the theory should also take into account the intentional attitudes of the actors, their Theory of Mind models and internal reasoning.

In his theory of Dialogue Gameboard, Ginzburg (Ginzburg & Fernández, 2010) instead of focusing on the intentional attitudes of the dialogue participants, considers the public and conventional aspects of communication. While this theory is useful for representing and formalizing conversations, representing an interaction between the actors in a complex, safety-critical STS as a conversational scoreboard that keeps track of the state of the conversation would be insufficient to capture the complexity of explicit and implicit coordination mechanisms, taking elaborated task programming mechanisms into account.

For our study, we selected the **Joint Activity (JA) model** (Klein et al., 2005), the **Co-ladder model** (Chow et al., 2000) and the **multi-agent situation awareness (MASA) model** (Blom & Sharpanskykh, 2015). The JA model introduced by Klein et al. (2005) forms an overarching, conceptual framework for modelling coordination which on a high level satisfies all the essential modelling desiderata identified above. The Co-ladder model of communication and coordination (Chow et al., 2000) further refines and operationalizes the central high-level concepts of the Joint Activity model into cognitive, behavioural, and environmental states, relations, and processes. Such a model is well-suited for formalization, which is then done using the MASA model (Blom & Sharpanskykh, 2015). Using a formal model, one can perform formal (automated) analysis of coordination processes and computer-aided simulation of diverse scenarios.

All three modelling frameworks are complementary to each other and need to be used in tandem. Such an integrative approach allows representing and reasoning about coordination at different levels of meaning and operationalization in complex safety-critical STS.

Moreover, the chosen models and theories are well aligned with other existing theories of coordination. The model by Klein et al. provides both depth and high level of generalization and is well aligned with Mintzberg's organization and coordination theory. We discuss in Section 2.8 in detail relations between concepts from Weick's sensemaking theory (Weick, 1995) and Co-ladder (Chow et al., 2000) and Joint Activity (Klein et al., 2005) model. Furthermore, the co-ladder model operationalized using the formal concept of multi-agent situation awareness (MASA) (Blom & Sharpanskykh, 2015) can be well related to relational approaches to coordination based on shared goals and shared knowledge, as described by Bolton et al. (2021).

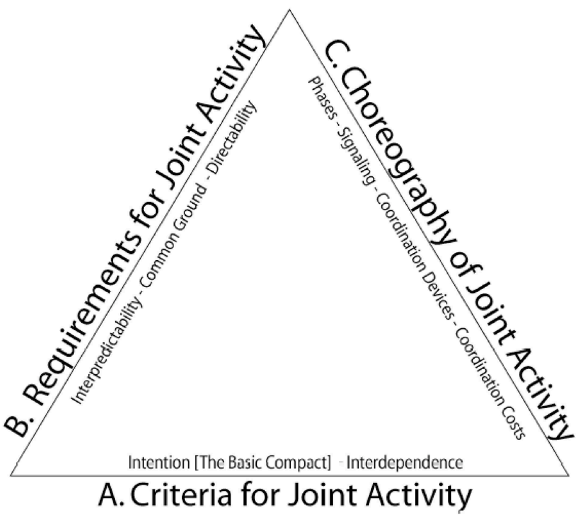


**Fig. 1.** The Joint Activity triangle. Reproduced from Klein et al. (2005).

*2.3. The Joint Activity model*

To understand coordination in complex STS, one can start by asking *why* must the agents coordinate? As mentioned in Section 2.1, coordination is the management of dependencies between tasks to achieve a common goal. Hence, having to be dependent on other agents in the team is essentially a criteria for coordination to take place. Klein et al. introduce the concept of Joint Activity (JA) (Klein et al., 2005) which is closely related to the concept of team coordination. Fig. 1 adopted from Klein et al. (2005) focuses on three main parts of JA. To enter a JA, the participants must satisfy the criteria. Once the criteria are satisfied, 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. JA forms the basis of our model, and is explained in more detail in the following.

**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.

**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. The participants of JA can perform many activities to support CG (Klein et al., 2005):

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

We discuss common ground further in Section 2.6. 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. In most of the cases, the tasks and activities are coordinated according to a prior agreement or pre-established convention etc. 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 been considered out of scope in our work.

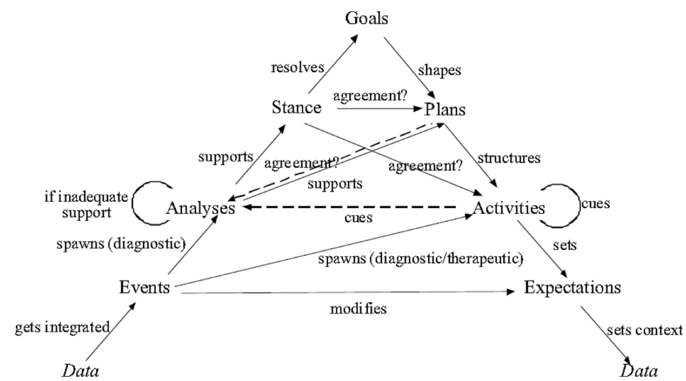


**Fig. 2.** Co-ladder model of coordination. Reproduced from Chow et al. (2000).

*2.4. Co-ladder model of communication and coordination*

Highly complex systems usually achieve coordination by high levels of standardization. There exist rules and regulations that govern their 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. Furthermore, too much reliance on standard practices might prove to be detrimental in an abnormal situation that requires a non-routine & creative solution (Grote et al., 2004). 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 formalizes how coordination occurs. It categorizes eight types of information that one agent (or team) can communicate to another and reason about (Chow et al., 2000). 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. All the coordination processes take place over a temporal (x-axis) dimension. Fig. 2 shows the co-ladder model reproduced from Chow et al. (2000). Along the y-axis of this model, the scale ranges from the causal nature of constraints to an intentional nature. The co-ladder model and the simple transitions between processes have been described below. Subsequently, Section 3.3.2 elaborates in detail these interactions and how they were used for analysis in this study.

**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 weather, 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, it forms an event. Usually, data gets integrated into an event over a period of time. 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 trigger analyses, specially if it is not an expected or known event. The analysis node encompasses the agent's observation and interpretation, 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. In complex systems, many parallel analysis processes 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 (Chow et al., 2000). A change of stance usually occurs because of a major shift in the agent's understanding, for example when new information becomes available. The stance can evolve goals, plans and also trigger activities.

**Goals:** Goals are at the highest level in the co-ladder model. 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 (Chow et al., 2000). 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. To resolve conflicts, 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. Planning also requires analyses, which not only helps forming plans but also evolving or altering plans as time progresses.

**Activities:** Activities include 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 set by the agent who performs the activity in relation to 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 formed regarding raw data and when it is observed that raw data deviates from the expectations, it constitutes an event.

### 2.5. Multi-agent situation awareness model

Formalizing coordination processes mathematically provides yet another lens to better account for human cognition within a sociotechnical system. A multi-agent system model could help in representing and understanding the complex dynamics of a system both retrospectively and by considering hypothetical scenarios. Therefore, in addition to providing clarity, such a model would allow us to inspect the effectiveness of coordination processes in different scenarios.

A central concept in agent-based modelling of sociotechnical systems is an agent's situation awareness (SA). Situation awareness is "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*" (Endsley, 1995). In simple words, it is an operator's dynamic understanding of "what is going on". There exist three schools of thought regarding 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 school of research regards SA as a combination of the product and the process. They describe SA as a *"generative process of knowledge creation and informed action"* (Blom & Sharpanskykh, 2015).

Recent developments in human factors research show 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 (Blom & Sharpanskykh, 2015). Blom and Sharpanskykh (Blom & Sharpanskykh, 2015) present a mathematical modelling framework for multi-agent situation awareness (MASA) relations. Their mathematical model supports all the three different schools of research on SA.

The framework considers a multi-agent system (MAS) of N agents $A_i, i = 1, \dots N$. 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 (e.g., noticing that it is raining outside or having experience in flying an Airbus A330). It is important to note that even non-human agents (such as the aircraft) can have state elements (known as base states, e.g., having the position of takeoff) 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 their other state elements or state elements of another agent, $A_k$. These MASA relations between agents are denoted 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 $\sigma_{t,i}^k$. As complex MAS are 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 an appropriate level of SA which will help in interacting and executing of activities. Finally, agents may also have state elements in the present regarding some future state of themselves or of other agents. These future-oriented state elements are called intents. An intent of an agent can be an expectation of another agent. Section 3.3.3 presents some elaborated examples using this formalization.

### 2.6. Common ground in coordination

Common Ground (CG) is essential for any kind of joint activity involving a team and multiple agents interacting within this team. Common ground is what makes coordination and joint activity work (Klein et al., 2005). The term, common ground, has been around for a long time and is now well incorporated in modern social psychology. According to Clark and Brennan (Clark & Brennan, 1991), *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 (Klein et al., 2005):

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*** - 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. (2005) have also identified the most important constituents of CG:

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.)

An agents' CG can have faults and breakages at any time between any number of agents. Hence the need for updating, monitoring, repairing CG arises. It is important to detect loss of CG before it turns into a serious accident from which recovery is difficult. It is therefore essential for the agents to be aware of the states regarding which they need to maintain or monitor common ground.

Multiple levels of CG and SA can be distinguished. Firstly, 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 another agent has an awareness about a certain state. This is 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.

### 2.7. Coordination breakdowns

Many factors can lead to a breakdown in coordination over time. When there is insufficient or incorrect CG between agents, the SA of the agents is also insufficient or unreliable. As time passes and situations alter, the CG of the agents will be compromised because not all agents will update similarly and interpretations may vary from person to person. Breakdowns usually do not arise from the absence of a shared understanding of a situation, they arise when an agent makes wrong assumptions about another agent (Klein et al., 2005).

Bearman et al. state that "*a breakdown occurs when there is a failure of coordinated decision making that leads to a temporary loss of ability to function effectively*" (Bearman et al., 2010). They surveyed the coordination and breakdowns between air traffic controllers, and the following causes of breakdowns have been identified (Bearman et al., 2010).

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.

Analyzing 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 (Blom & Sharpanskykh, 2015). In a system, a 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. Usually, explicit communication can repair and restore common ground. This also becomes more challenging if a geographically or culturally diverse team is coordinating. The more a team coordinates, the better it will coordinate as time passes.

Klein et al. have identified several reasons that contribute to the loss of common ground between agents engaged in a joint activity. These are: lack of experience in working together, access to different data, unclear rationale for assigned tasks, ignorance of differences in stance among team members, unexpected lack of communication (and the inability to repair this problem), failure to monitor communication confirmation and confusion over who knows what (Klein et al., 2005). 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 it should have) and it fails to detect his loss of CG, the other agents will still assume it has CG and will proceed accordingly. Only when this particular agent will fail to deliver (or do) something that it must, the coordination breakdown is detected and can be repaired, and the coordinating process can continue.

### 2.8. Sensemaking

The concept of sensemaking (Weick, 1995) is closely related to the concepts of MASA, CG and coordination. Sensemaking, just like coordination, occurs everywhere and is tested to the maximum when things are not going as planned or expected. All coordination, including the frameworks used in this research project, can be broadly placed under the umbrella of sensemaking. Coordination comprises of observation, analysis, planning and re-planning, acting (saying or doing), feedback and reacting and so on. All of these can be seen as part of the sensemaking process as well. Karl E. Weick explores in detail the properties of sensemaking (Weick, 1995): sensemaking is grounded in identity construction; it is always ongoing, retrospective and has the social dimension; cues extracted by agents from their environment are crucial to sensemaking and they lead to action.

Building of Weick's ideas, Sieck et al. (2007) further elaborated sensemaking from a cognitive perspective in the Data/Frame model. Frames are stable cognitive constructs through which an individual is able to understand the situation. This model comprises six temporally-related sensemaking functions: (1) constructing and elaborating a frame using data gathered from a situation, data stored in the frame, and data inferred from both; (2) questioning the frame if observed data do not match a frame; (3) preserving the frame when a justification for inconsistencies is found; (4) comparing alternative frames that fit the situation; (5) selecting a relevant frame to generate an explanation to the situation; (6) reframing by recognizing the importance of new data and discarding unnecessary, irrelevant data, which were previously considered as important. Note that sensemaking is not only about the understanding of the situation, but also about what an individual is able to do in a situation. Therefore, sensemaking involves reasoning about goals, plans and activities. The Data/Frame model can be well related to the co-ladder model, in which the individual analyses data and events to understand the situation and form a corresponding stance, which could be questioned by considering new data. By changing the stance, individuals could reconsider their goals, plans and activities.

## 3. Formal modelling of coordination

Safety-II approach towards understanding ATM safety focuses on understanding and enabling everyday success. This approach encourages us to assess safety by the measure of frequent successes and not by the occurrence of a (rare) accident event. Air transportation is 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 when there is no failure or accident? We aim to address this knowledge gap and, in this section, we elaborate the steps we took to meet our aim.

### *3.1. Step 1: Selection of frameworks for analysis*

Section 2 lays out the three different frameworks that have been selected for the purpose of this research. These are; a) the Joint Activity model (Section 2.3), b) the co-ladder model (Section 2.4) and c) the multi-agent situation awareness (MASA) model (Section 2.5). These frameworks provide three different understandings, on varying abstraction levels, of coordination in STS. 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 STS. The Joint Activity model by Klein et al. (2005) that we chose as the basis provides both depth and high level of generalization and is well aligned with other more high level theories such as Mintzberg's organization and coordination theory (Mintzberg, 1989) and Weick's sensemaking theory (Weick, 1995). In particular, we discussed in detail relations between concepts from Weick's theory (Weick, 1995) and co-ladder (Chow et al., 2000) and JA model (Klein et al., 2005). At the same time, Klein et al.'s theory (Klein et al., 2005) is more detailed and can well be formalized and operationalized.

### *3.2. Step 2: Selection of an aviation case*

To study coordination, we can select any day-to-day operational records (transcripts or tapes) as coordination does take place always. Such data is however difficult to obtain. We instead focus on accident cases, the corresponding reports and transcripts of which are publicly available. The following criteria was enforced when selecting a case:

1. Non-nominal accidents cases that cannot be traced back to one failure (such as a mechanical faults) but instead was a result of a series of events that couldn't have been predicted.
2. Cases attributed to "human errors" like misinterpretation, miscommunication or use of wrong terminology.
3. Cases that involve other human factors like stress, distraction, confusion or forgetfulness.

We selected the Tenerife airport crash that took place in 1977.

*Case study: 1977 Tenerife runway collision*

On March $27^{th}$ 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 were redirected to Las Rodeos airport located in Tenerife in the Canary islands. The Las Rodeos airport (now called the Tenerife North airport) was 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. During the considerable waiting period at Las Rodeos airport, the KLM staff had let the passengers disembark and the KLM captain had decided to fully refuel the KLM aircraft. He did this mainly to eliminate the need to refuel at Las Palmas in order to save time because he wanted to reach their final destination (Schiphol Airport) before he exceeded his (then recently imposed) Dutch duty-limits. Eventually, the Las Palmas airport was again functional and flights started to takeoff to their original destinations. During this time, the PA aircraft was forced to wait behind the KLM aircraft while it refuelled and re-seated all its passengers. This

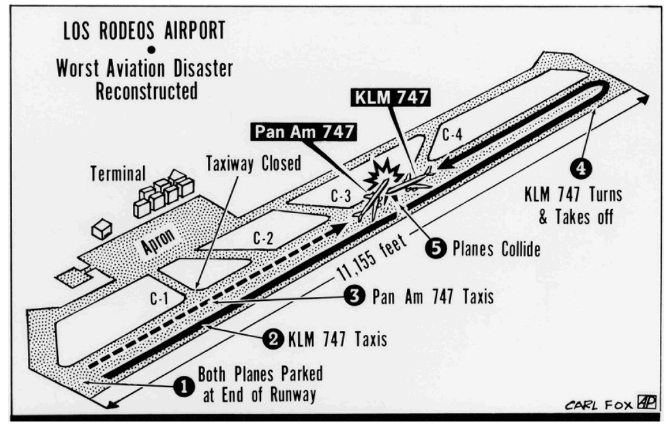


**Fig. 3.** Reconstruction of the Tenerife airport KLM-Pan Am collision on $27^{th}$ March, 1977.

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. As 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 clear KLM for takeoff once the PA aircraft had exited through taxiway C3, following which the PA 747 could also takeoff. Ultimately, however, the KLM crew began to takeoff while the PA aircraft was still on the runway resulting in a head-on collision.

Fig. 3 shows a simplistic reconstruction of the Tenerife airport and how the aircraft moved around this airport space, to finally collide. This is said to be 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 a sequence of events that led to that unfortunate moment. The probable causes and influencing factors established by the joint official report of the Spanish Government (Government of Spain, 1978) and the accident report of the Airline Pilots Association (Airline Pilots Association, 1977) are summarised below:

1. KLM captain took off without takeoff clearance. He did not obey the controllers instruction to "stand-by for takeoff" and he did not interrupt the takeoff on learning that the PA aircraft was still on the runway.
2. Growing tensions among the KLM crew due to the KLM captain having to grapple with the strict Dutch duty-limits.
3. Development of a false hypothesis due to behavioural conditioning as a result of nearly constant exposure to the training environment or "training syndrome".
4. Sudden reduction of visibility and total loss of visual contact prior to takeoff.
5. Malfunction of the radio in the KLM cockpit for 3 seconds (caused due to Air Traffic Controller and PA-CREW speaking simultaneously) resulting in KLM crew not hearing a crucial instruction.
6. Other factors: Use of non-standard terminology, language-barriers, stress, confusion over taxiways and exits, small airport accommodating many more and larger aircraft than it was efficiently capable to handle.

The various causes and influencing factors provide an idea of how an hazardous situation could have been created. There remain some questions such as; if the KLM captain began take-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?

The transcripts from the aircrafts' Cockpit Voice Recorder (CVR), as presented in the official joint report (Government of Spain, 1978), are used for analysis. The transcript[1] constitutes the final eight minutes before the collision (when the KLM aircraft starts taxiing). The transcript shows 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 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. **KLM-C** - The KLM Captain has been identified as an agent for a specific part of the analysis where he acts separately from the KLM-CREW.
3. **KLM-RF** - This agent represents the rest of the KLM-CREW when KLM-C acts as a separate agent from KLM-CREW. This agent refers to the KLM First Officer together with the KLM Radio engineer and has been identified as an agent for a specific part of the analysis.
4. **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.
5. **ATCO** - The air traffic controller at the Tenerife tower who was in direct contact with KLM and PA crews is identified as one agent.
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.

### 3.3. Step 3: Applying the selected frameworks to the case

The three selected frameworks (the Joint Activity model - Section 2.3, the co-ladder model - Section 2.4, the multi-agent situation awareness model - Section 2.5) are applied to the selected case. We implement the frameworks together thereby integrating their different levels of abstraction in the understanding of coordination, including a mathematical formalization. We explain below how these frameworks were used to analyze coordination in the last eight minutes before the crash occurred.

#### 3.3.1. Meeting the conditions of coordination - the Joint Activity model

We begin with fundamental questions like why does this team need to coordinate? and can this team coordinate? The Joint Activity (JA) model (Fig. 1) (Klein et al., 2005) can be used to answer these questions methodically as follows:

***Criteria for Joint Activity.*** The two main criteria for a JA are that the agents must want and need to coordinate with each other. Hence, this is about the agents' intentions and their interdependencies. The agents must intend to work together and should also have interdependencies among them, that raise the need for them to coordinate. In coordination in complex STS, 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. A similar situation exists in our selected case because all the agents are performing their jobs but they want and need to be working together to achieve effective aviation operations. In this 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 be analysed to see if the agents' intentions or interdependence vary.

***Requirements for Joint Activity.*** JA requires that the agents can actually coordinate in a meaningful and efficient way. In complex STS, the requirements may 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 make their own actions predictable. This is usually enabled by standardization, in one form or another (Section 2.3). 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 itself 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 an 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. 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 incorrect 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 it 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 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.*** 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 which highlight aspects such as phases or coordination, signalling, coordination costs etc.

[1] A compiled version of the transcript can be found here: https://www.pbs.org/wgbh/nova/article/final-eight-minutes/ Alternatively, a stable version is available via the Internet Archive at: https://web.archive.org/web/20260801220809/https://www.pbs.org/wgbh/nova/article/final-eight-minutes/

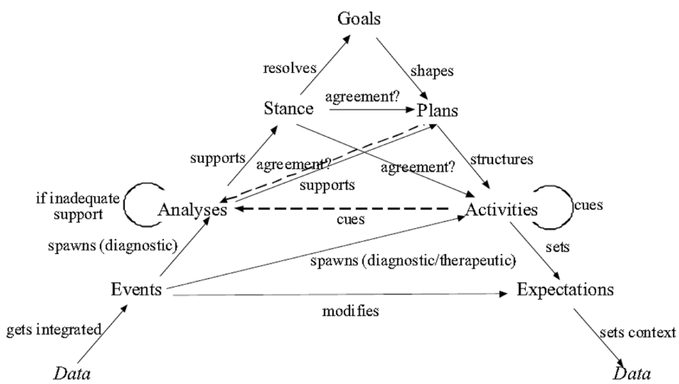


**Fig. 4.** The functional model of communication and coordination during distributed anomaly response. Reproduced from the work of Chow et al. (2000).

In this study, these aspects of coordination have been identified but are not the central focus.

*3.3.2. What goes on inside an agent's mind? - the Co-ladder model*

Once we know why and how agents interact and coordinate within a team, we proceed towards understanding what happens in an agent's mind when they are coordinating. The mental processes are implicit and commonly not recognised by the agents themselves. Understanding these processes at every time-step in this study, requires to make assumptions about the thought processes of the agents underneath their actions/words. Fig. 4 shows the functional model of communication and coordination for distributes anomaly response in complex STS (Chow et al., 2000). This model helps to formalise human cognition by modelling how a person 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 (such as operating safely) and perform every other action in-line with these shared goals. However, the goals do not remain unaffected. A major change in context in some situations can lead to the modification or rejection of a certain goal. As seen in Fig. 4, goals shape plans and can be resolved when a stance changes.

**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 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 unexpected occurrence which can raise the need for modification of priorities and actions. On the other hand, expectations are 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 are met. If they were not, it constitutes an event and might possibly trigger an analyses.

*3.3.3. Mathematical formalization - multi-agent situation awareness model*

Agent-based modelling of coordination creates a more specific understanding of coordination mechanisms as it enables analysis by simulation. Several aspects of common ground (CG), like maintenance, updating, loss and repair, can be identified and analysed when modelled. Mathematical modelling and simulation provides the opportunity to validate our understanding of coordination mechanisms, also in variable scenarios, and help is developing predictive capabilities.

Common ground is crucial in multi-agent situation awareness. While situation awareness is 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. To formalise common ground, the MASA framework (Blom & Sharpanskykh, 2015) is used. The MASA model can be applied to a multi-agent system with N agents. 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, only about 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 (Section 2.5) 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, 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 its 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.
- $S_{PA-CREW}^{ATCO}$ = [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 structured data is suitable for mathematical modelling. The mathematical formulation will complement the first two frameworks and create a more complete understanding of coordination mechanisms. 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. (2010) is used to describe and categorize the coordination breakdown, propagated by the loss or common ground, in this study.

### 3.4. Step 4: Analysis

A matrix was created to show the implementation of the three frameworks - constituting an agent-based model (see Section 4.4). The autonomous agents were introduced in Section 3.2 and their cognitive and behavioural properties were specified using the co-ladder model (Chow et al., 2000) and the MASA modelling framework (Blom & Sharpanskykh, 2015). This matrix, an instance of which is seen in Table 6 in Section 4.4, is analysed to better understand how common ground is effected in coordination. The following Section 4 provides a detailed account of these results. Coordination mechanisms are 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 4.6.

For validating our mathematical model, we used temporal-trace language (TTL) specifications and simulated it using agent-based software known as LEADSTO (Language and Environment for Analysis of Dynamics by SimulaTiOn). The formal modelling language is a variant of an order-sorted predicate logic with the possibility to express causal, temporal relations. However, such languages are often used for specifying agent-based models (Jamroga & Penczek, 2012). This software has been developed to model the dynamics of multi-agent 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, described in detail in Section 4.7 along with examples of the specifications used. Once a mathematical model is constructed, the LEADSTO software environment[2] can be used to run simulations (Section 4.8).

The developed model can be used for both retrospective analysis and for prospective analysis. In such a way, we analyzed the emergence of losses of common ground, their identification, propagation and repair in two variations of the main use case (Section 5). We used the agent-based model developed for the main use case and changed only the environmental conditions and observations available to the agents. The model dynamics were evolving by activating cognitive and behavioural properties of the agents, which corresponded to the new situation. In such a way, we observed different emerging dynamics in all these cases. Implementation of identified coordination mechanisms and variability analyses was done to check for validity (Section 5).

## 4. Results

This section presents the results of applying the three frameworks on the CVR transcript (Government of Spain, 1978; Krock, 2006) of the Tenerife airport crash of 1977. We begin by describing how each of the three frameworks are applied to our case study. Firstly, using the Joint Activity triangle we can identify if and how the criteria and requirements for a joint activity are fulfilled by agents (Section 4.1). Then we formalize the agents' coordination and communication using the Coladder model and map out various interaction patterns (Section 4.2). Lastly, state elements were identified (continuous, discrete and intent) in order to mathematically model the case study (Section 4.3). In Section 4.4, we present an instance of these implementations together in one matrix.

### 4.1. Framework 1: Joint Activity triangle

The JA framework is used to identify if the agents of our use case meet the criteria for a joint activity, i.e. do they have the intention to work together and whether there exist interdependencies among them.

[2] Available at: https://www.few.vu.nl/~wai/TTL/ Alternatively, a stable version is available via the Internet Archive at: https://web.archive.org/web/20240421152738/https://www.few.vu.nl/~wai/TTL/

1. **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. These intentions of the agents are assumed to be constant and therefore are not represented in the matrix in Section 4.4.
2. **Interdependencies** -
   - 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.
   - 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.

Next, we use the JA framework to assess whether the JA requirements of interpredictability, common ground and directablity are met and in what way.

1. **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
2. **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.
3. **Common Ground** – Common ground plays a crucial role and is the main focus of this thesis and is discussed in detail in Section 4.5.

Lastly, to formally map out the choreography of a joint activity, the following co-ladder framework is used.

### 4.2. Framework 2: Model for communication and coordination

The co-ladder model is used to identify actions and communication for every step in the CVR transcript of the 1977 Tenerife crash. The first step is to identify the goals, plans, activities, expectations, events, analyses and stances of various agents in the case study. Table 1 shows some of the identified elements and all the identified elements have been listed and described in A. 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 in the case study, the model of communication and coordination (see Section 2.4 and Fig. 4) is used to discern the flows of interaction between these different elements for each agent. Several relational patterns of communication and coordination were identified:

1. Agents' goals (G) shape plans (P) which structure activities (A) and set certain expectations (E). For example, the KLM crew has a goal to take of ASAP (G1) and a goal of safe and efficient operations (G2). This shapes the plan to backtrack following aviation protocol (P1). This Plan P1 leads to an Activity A1 (the utterance "Approach KLM 4805 on the ground in Tenerife") which creates an expectation E1 on the part of the KLM crew that ATC will acknowledge the attempt to establish communication. This is represented in the following way: (KLM-CREW) : G1 & G2 → P1 → A1 → E1
2. An activity (A) might cue multiple activities (A) and/or analysis (An) etc. and similarly, an analysis (An) may give rise to plans (P) and activities (A). For example, agent ATCo plans for the KLM aircraft to backtrack on runway 30 (P5). KLM-CREW, following Plan P5, informs ATCo of their position on the runway ("I think we just passed Charlie 4 now") - constituting Activity A24. Hearing this triggers an Analysis An7 on the part of ATCo which leads to the formation of the next part of the plan - Plan P9. P9 requires the KLM aircraft to turn 180 at the runway end and report back requesting for ATC clearance. ATCo informs the KLM-CREW of Plan P9 - constituting Activity A25. This is represented in the following way:
   (ATCo) : P5 $\xrightarrow{A24}$ An7 → P9 → A25
3. For the regular communication requiring no (substantial) analysis, the simple "Activity – cues – Activity" pattern is applicable; specially for communications that are about acknowledging a previous message. For example, agent PA-CREW receives a communication from ATCo to "taxi into the runway and - ah - leave the runway third, third to your left" - constituting Activity A18. This activity triggers two subsequent activities from the PA-CREW: they begin to taxi down the runway behind KLM (A19) and they respond to ATCo stating "Third to the left, okay" (A20). They respond because they are following Plan P8 which requires them to respond to certain communications. This is represented as follows:
   (PA-CREW) : P8 $\xrightarrow{A18}$ A19 & A20
4. Sometimes communication requires interpretation and analysis of received information, where the "Activity (Input msg) – Analysis – Plans – Activity (Output msg)" relational pattern fits best. For example, while following Plan P3, agent ATCo receives communication from the KLM-CREW stating that they were "(entering) the runway at this time and the first (taxiway) we, we go off the runway again for the beginning of runway 30". This communication constituted Activity A6. Hearing this, ATCo realizes that the KLM-CREW has interpreted the Plan P3 incorrectly. This process makes for Analysis An3. Based on this analysis, ATCo formulates a new plan - Plan P5 and communicates it to the KLM-CREW as Activity A7. See below:
   (ATCo) : P3 $\xrightarrow{A6}$ An3 → P5 → A7

**Table 1**
The identified elements.

| 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 2**
Continuous valued state elements.

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

5. Activities always set an expectation for a time in the future, usually involving another agent. For example, agent KLM-CREW does Activity A12 (asking ATCo "Approach, you want us to turn left at Charlie 1, taxiway Charlie 1?") and an Expectation E12 (of hearing a confirmation of taxi instructions) is set. This is represented as:
(KLM-CREW) : A12 → E12

These relations are represented at every time step in the matrix in Section 4.4. Identifying such relational patterns is important because they bring an understanding and formal interpretation of human behaviour and human-machine interaction within complex sociotechnical contexts. This knowledge helps in identifying important coordination and communication patterns and creating systems that enable these patterns, hence contributing to safer outcomes. A formal expression of human coordination can use used to create mathematical models (Section 4.3 below) with more accurate predictive capabilities, ultimately contributing to safety efforts.

### 4.3. Framework 3: Multi-agent situation awarenness (MASA) modelling

The first step in using the MASA framework (Section 2.5) is to identify the state elements. The state elements identified here overlap with the identified elements, such as those presented in Table 1. This is because both these frameworks seek to formalize human coordination, and the MASA framework goes a step further to create a mathematical model. For this, three types of state elements are identified: continuous, discrete and intent. Table 2 shows a few of the identified continuous valued state elements. As described earlier in Section 2.5, these states are usually changing over time and provide quantifiable information. In the present case study, the position of the two aircraft are the only state elements of the crews of the two aircraft which are relevant.

Discrete states, as the name suggests, are those states of agents that take discrete values, e.g., limited set of real numbers. For our case study, many discrete states can be identified for different agents. The most essential discrete state elements of the agents have been demonstrated in Table 3. Table B.21 shows all of the identified discrete states.

Apart from the three main agents mentioned in Table 3, 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 non-agents themselves does not have an awareness about this state. For example, an airport will not have any awareness about its own visibility conditions. Table 4 presents the main discrete state elements of the several other identified agents.

Finally, all proactive agents also have intent valued state elements. These are the states that correspond to a time step in the future. These states can represent a plan that is to be followed by the agent at a certain time in the future 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 future-oriented states, some of which have been presented in Table 5 below (assuming the current time as $t$).

### 4.4. Modelling coordination: Implementing the three frameworks in one matrix

Table 6 shows the implementation of the three frameworks for time steps $t12$ and $t13$ from the CVR transcript. The mathematical modelling of these elements provides a systematic formalization of the human cognition and interaction within the sociotechnical setting of the case study. Every proactive agent has a certain awareness about itself, its environment and other agents. Common ground is achieved between two or more agents if their awareness regarding a certain state is "common" or congruent. Such a formalization, therefore, helps to identify specific coordination mechanisms pertaining to the ways in which agents can lose, identify the loss, and repair the loss of common ground.

We implement the previously described three frameworks in one matrix. Every time step of the case transcript is modelled using each one of the three frameworks to disentangle and formalize the underlying coordination processes, see Table 6. The first column shows the agent's communication as per the CVR transcript for every time step. The second column presents the theoretical understanding of the action at that point in time using the JA triangle which inspects the interaction among agents. The third column presents the cognitive processes of the agents modelled using the co-ladder framework. The last column uses ABM techniques from the MASA framework to formalise each interaction. Additionally, assumptions were made to fill in the gaps since the official records showed what happened from an external point of view (mainly audio communications) and the internal reasoning is not explicit:

1. All crews and controllers are trained and committed to following standard aviation protocols and aim to perform safe and efficient operations.
2. The aircraft begin taxiing as soon as their crews receive their respective taxi clearances.
3. The KLM-CREW interprets the provision of ATC clearance as an ATC clearance and the provision of takeoff clearance at the same time, thereby initiating takeoff without requesting proper clearance.
4. The KLM-CREW assumes that the PA aircraft is off the runway when they are provided with the ATC clearance as they do not hear PA-CREW's report of their position being on the runway.

### 4.5. Analysis of the coordination model

Analysis of the model of coordination (Table 6) to better understand Common Ground (CG) was considered from three perspectives; CG that

**Table 3**
Discrete valued state elements, part 1.

| 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 4**
Discrete valued state elements, part 2.

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

**Table 5**
Intent valued state elements.

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

**Table 6**
Implementation of the three frameworks in one matrix - excerpt showing coordination modelling for *t*12 and *t*13.

| Coordination | Joint Activity | Co-ladder | MASA |
|---|---|---|---|
| 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.<br>**Interpredictability** – KLM-CREW reconfirms its plan with ATCo, so that ATCo would be able to guide KLM safely and effectively.<br>**CG** – KLM attempts to re-confirm CG regarding taxi instructions.<br><br>Coordination device – **signalling** – direct reconfirmation of plans. | **KLM-CREW**<br>P4 → A12<br>A12 → E12 | $f^{r}_{KLM-CREW}$ (plan(P4))<br>$[\sigma^{KLM-CREW}_{t12,ATCO}; \sigma^{ATCO}_{t12,KLM-CREW}]$<br>$= f^{mi}_{KLM-CREW,ATCO}$(reconfirming plan(P4))<br>= [plan(P4) ; expectation(E12, t12 + 5)] |
| 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 ins-tructions to the KLM-CREW, working to achieve the same goal.<br>**Interpredictability** – ATCo expects KLM-CREW to ack-nowledge the repeated taxi instructions. ATCo repeats plan to enable predictability.<br>**CG** – ATCo attempts to re-establish CG regarding taxi instructions with KLM-CREW.<br>**Directability** – Repeat correct instructions through direct radio.<br>Coordination costs – time, over (extra) communication.<br><br>**Coordination breakdown** – detected by ATCo with KLM– It is a breakdown because of **language** – misunderstanding the intent of others. | **ATCo**<br>P5 $\xrightarrow{\underline{A12}}$ A13<br>A13 → E13 | $f^{r}_{ATCO}$(plan(P5), $\sigma^{KLM-CREW}_{t12,ATCO}$)<br>$[\sigma^{ATCO}_{t13,KLM-CREW}; \sigma^{KLM-CREW}_{t13,ATCO}]$<br>$= f^{mi}_{KLM-CREW,ATCO}$(repeat plan(P5))<br>= [plan(P5) ; expectation(E13, t13 + 5)] |

is updated and 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. Table 7 presents what common ground is updated at every time step, and how. It shows the loss of common ground (both detected and undetected) at each time step, if any. Lastly, Table 7 also shows the states regarding which agents should maintain, monitor or update CG as time passes. 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.
- ATCo's intent to know the dynamic states of aircraft with timely updates.
- Aircraft crews' intent to know if the controller knows their position after they reported it; this is a second level awareness on the part of the crews.
- In certain situations, it is crucial for the ATCo to know that the aircraft crew knows that the ATCo knows their report of a dynamic state; this is a third level of awareness on the part of the controller.

**Table 7**
Common Ground analysis, excerpt showing analysis for $t12$ and $t13$.

| Time | CG maintained and updated | CG that agents (are supposed to) monitor and sustain | CG loss |
|---|---|---|---|
| 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) |

- 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).

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 monitor this CG unless a major stance change occurs. With that in mind, Table 7 is structured as follows:

1. The first column shows the communication from the CVR transcript of the case study, and each time step corresponds to the time step number and the activity number.
2. The second column only shows the states regarding which agents $i$ and $k$ have maintained common ground at that time. Hence, this column primarily lists all the CG updates that occur at every time step.
3. The third column shows the states that the agents are supposed to be monitoring to perform this joint activity. Agents monitor these states to maintain interpredictability (as described in Section 2.3) by being able to anticipate the future states of other agents along with making ones own states predictable for other agents, and in order to set expectations and check if these are met (as described in Section 2.4). 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.
4. 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".
5. 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 explicitly pointed out in Table 7.

### 4.6. Identifying mechanisms

Based on the resulting matrix and the analysis of common ground, several generic coordination mechanisms have been identified. These mechanisms have been determined 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 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.

Some generalizations can be made in terms of the mechanisms used to identify loss of CG loss. Table 8 presents these mechanisms and Table 9 shows which mechanisms are used by which specific agents.

Other generalizations can be made in terms of the coordination mechanisms used by the controllers for the repair of CG loss as opposed to the ones used by the crews. Table 10 presents these mechanisms and Table 11 shows which mechanisms are used by specific agents to repair the loss of CG.

#### 4.6.1. Probable causes for the loss of CG

The loss of common ground can occur due to many diverse reasons ranging from inexperience to anger, exhibited by a human agent. 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 resulting matrix, using the framework provided by (Bearman et al., 2010) 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.

**Table 8**
Mechanisms for the identification of the loss of CG.

| 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** | Indirect identification via inference based on communicated states by other agents. |
| **D4** | An observed or communicated state does not correspond to the expected state of an agent. |
| **D5** | The intent to repeat important parts of the information without a request to do so. |
| **D6** | 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). |
| **D7** | Tone of voice and "how" something is communicated (unsure communication). |
| **D8** | Explicit discussion or reasoning within a team can also reveal inconsistencies in CG, particularly exchanges of information on stances between team members. |
| **D9** | When agents can recognize that certain information has expired. |
| **D10** | When a certain information uncertainty has reached a certain threshold. |

**Table 9**
CG loss identification mechanisms used by specific agent groups.

| CREWS | ATCOs |
|---|---|
| By observation against expectation By requesting repeat of some information (such as a plan) 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 |

3. Environment and technology
4. Human memory
5. Attention
6. (Incorrect) expectations.

### 4.7. Modelling in LEADSTO

We structured the specification of cognitive, behavioural and interaction properties of the agents based on the Co-ladder (Chow et al., 2000) and MASA (Blom & Sharpanskykh, 2015) modelling frameworks. This was used as the basis for modelling coordination for our selected event. These existing modelling frameworks provide a structured approach to define the local properties of agents and their interactions, which we followed. Then these properties were formalized using the LEADSTO language. The LEADSTO software environment[3] was used for simulation of the use case.

*ODD Protocol.* Here we present the Overview, Design concepts and Details (ODD) protocol which is used for describing Agent-Based Models (ABMs) (Grimm et al., 2020).

1. **Purpose and patterns**: The main purpose of the simulation model is to enable analysis of different variations of the main scenario and perform a face value validation (see Section 5). For our study, the ABM was considered sufficiently realistic when the temporal trace pattern from the LEADSTO simulation matched the event log pattern of the CVR transcript (Government of Spain, 1978; Krock, 2006).
2. **Entities, state variables and scales**: The model represents human and non-human agents, identified in Section 3.2, namely KLM-CREW, KLM-C, KLM-RF, PA-CREW, ATCO and TNR. Using the MASA framework (Blom & Sharpanskykh, 2015), continuous (Table 2), discrete (Table B.21) and intent (Table B.22) valued state elements have been identified for each agent. The temporal resolution of the model is 1 second.
3. **Process overview and scheduling**: The processes in the model, i.e. which entities do what, when and the updating of their state variables, are defined based on the CVR transcript (Government of Spain, 1978; Krock, 2006) of the event. This is modelled using LEADSTO simulation software[4] which makes use of a temporal trace language (TTL). TTL models temporal dependencies between two state properties in successive states (known as dynamic properties) (Bosse et al., 2005). 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 $t$, which are used to represent the state elements. All 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 (Bosse et al., 2005). A state $S$ indicates which state property is true and which false: S: APROP(Ont) → [ true, false ]. The format has been defined as follows:

[3] Available at: https://www.few.vu.nl/~wai/TTL/ Alternatively, a stable version is available via the Internet Archive at: https://web.archive.org/web/20240421152738/https://www.few.vu.nl/~wai/TTL/

[4] Available at: https://www.few.vu.nl/~wai/TTL/ Alternatively, a stable version is available via the Internet Archive at: https://web.archive.org/web/20240421152738/https://www.few.vu.nl/~wai/TTL/

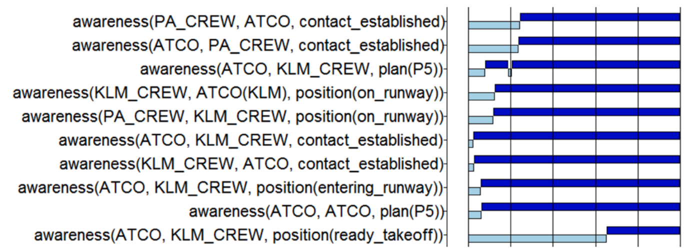


**Fig. 5.** A (partial) snapshot of the temporal traces from the final simulation.

Let $\alpha$ and $\beta$ 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 $\alpha$ holds true for a certain time interval with a duration of $g$, then after some delay (between $e$ and $f$) the state property $\beta$ will hold true for a certain time interval of $h$ duration.

4. **Design concepts**: The concepts underpinning the model include emergence, objectives, prediction, sensing, interaction and observation. We aimed to analyze the emergence of losses of common ground, their identification, propagation and repair in two variations of the main use case. To this end, we used the agent-based model for the main use case and changed only the environmental conditions and observations available to the agents. The agents have goals (Table A.14) that they pursue. The agents communicate with each other (Table A.16) and analyze these interactions (Table A.19) which sets their expectations (Table A.17) for future activities. The model dynamics were evolving by activating cognitive and behavioural properties of the agents, which corresponded to the new situation. In such a way, we observed different emerging dynamics in all these cases.
5. **Initialization and input data**: The model was initialized using event log of the main use case as the input data. Using the format presented above in point 3, LEADSTO specifications can be written for each time point in the selected accident event. These specifications can be directly derived from the formalization obtained by implementing the MASA framework (Blom & Sharpanskykh, 2015), using the identified state elements of agents as transitions between states. For example, below are the set of equations obtained using the MASA framework to depict ATCo's acknowledgement to KLM-CREW's position report:

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

The LEADSTO specifications for the same would be;

*has_plans(ATCO, ATCO, P5)* and 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)))*

### 4.8. Simulation in LEADSTO

Once the LEADSTO specifications have been modelled for all temporal dependencies between agents, the simulations are executed[5] The software produces a graphical output in the form of simple temporal traces. Fig. 5 is a partial snapshot from the final simulation of the accident case and depicts a small fraction of the complete temporal trace

[5] The complete source code of our simulation model has been made available.

**Table 10**
Mechanisms for the repair of the loss of CG.

| 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 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 11**
CG repair mechanisms used by specific agent groups.

| CREWS | ATCOs |
|---|---|
| By confirmation of a plan | By (solicited/unsolicited) repeat of a plan |
| By acknowledging an instruction | By requesting a state update |
| By observation | By informing |
| By explicit declaration of a state | By observation |
| By requesting repeat of some information (such as a plan) | |

produced. This part of the trace shows certain situational awareness 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, the agents' awarenesses that stay true through the entire time once they are established, have been shown. For example, Fig. 5 shows that both the KLM and PA crews are aware that they have established contact with ATCo, and ATCo is aware that they have established contact with the KLM and PA crews. This awareness does not change during the simulation because no such event that breaks established contact occurs.

## 5. Face value validation

With the working model completed, the face value validation was performed by the first author and verified by the research team. The LEADSTO simulation model was considered sufficiently realistic for the original case when the temporal trace simulation pattern matched the pattern of the event transcript logs. This was manually verified. Specific coordination mechanisms (Tables 12 and 13) were implemented in the model to analyze their effects on the coordination within the system. Alongside verifying if the mechanisms indeed work like we would expect them to, we also focus on the emergent effects that such an implementation could produce. Specifically, we focus on analysing how the coordination mechanisms would enable common ground, detect loss of CG and also repair the loss of CG.

The main purpose of the simulation model is to enable analysis of different variations of the main scenario. Two variations of the case (Sections 5.2) were chosen for the face value validation. In the first variation scenario we changed the environmental conditions in the agent-based model, and in the second variation scenario we changed the observation modalities of the ground controller through the availability of the ground radar. We analyzed the emergent dynamics based on these alterations, the results of which are described in Sections 5.2.1 and 5.2.2.

### 5.1. Original case

Selected mechanisms from the identified coordination mechanisms in Section 4.6 have been implemented in the model of the accident case and the following Tables 12 and 13 demonstrate the obtained results. The first column explains the mechanism used, the second column specifies the agent which applies 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 fourth 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 could be most useful. It is quite natural 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, although basic, still necessary. It is also important to note that the use of these mechanisms will not always lead to what is expected. Ultimately, it is about identifying important coordination mechanisms and supporting these in the context of human-human and human-machine interaction so as to enable safe aviation operations.

There always exists some uncertainty in real-world operations, such as unpredictable weather, health issues, sabotage etc. Supporting the coordination among agents can only ensure safe operations to a certain extent. Beyond that, we must rely on human ingenuity, adaptability, and resilient systems. Some important takeaways from this exercise have been enlisted below.

1. An agent's use of a certain coordination mechanism often leads to other agents' identifying and repairing their CG loss.
2. 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 one's state work 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 useful unless another agent is informed of this and this CG loss is then actively repaired. An agent must be aware that there exist unknown unknowns and have the ability of recognizing and reporting ignorance when relevant.
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 be useful in times when certain agents must not take any action, like no clearance for takeoff.
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. Furthermore, creativity and passion continue to be human attributes for the foreseeable future. The importance of this capability must be acknowledged and utilized.

### 5.2. Variations of the case

The first step towards a more extensive validation of these coordination mechanisms would be to imagine their use in other scenarios and observe their effects on the coordination with the system. Such an exercise can provide a better yet understanding of these coordination mechanisms. To test this, two fundamental variations were introduced

**Table 12**
Implementation of mechanisms, page 1.

| 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 do not wrongly assume that PA-CREW is off the runway. |

**Table 13**
Implementation of mechanisms, page 2.

| 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 assumption 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 infrastructure 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 important 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. |

in the original case study scenario to see how the identified coordination mechanisms would affect the coordination within this new sociotechnical system.

The first variation alters the visibility conditions. In the original scenario, the runway visibility conditions deteriorated from $2-3km$ to $300m$ in about 10 mins. This happens as the KLM aircraft began taxiing down the runway. The first variation is such that the visibility conditions remain good during the entire period of the official transcript. The second variation introduces ground radar, a standard equipment used around the world at all airports today, to aid the ATCo in his operations. 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 and in this scenario. The following mechanisms were implemented for testing the variations of the original model:

- Request repeat of information in case of disturbance, illegible audio, mishearing, wrong/unclear terminology 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.
- Repeating crucial parts of the plan, unsolicited. (D6) - applies only to ATCo.

#### 5.2.1. *Variation 1: Good visibility conditions*

This essential change to the original case is chosen because weather conditions can present many uncertainties in aviation operations and would be helpful to investigate how the coordination mechanisms would work under different weather conditions. Additionally, under nominal weather conditions, we can now focus on the basic coordination pertaining to operations when all agents have the required visual data. The aforementioned coordination mechanisms D6, D7 and R3 are implemented and they work as expected. Visual observation repaired many CG losses among agents, however, it also led to redundancy of using many coordination mechanisms. Under high runway visibility conditions, visual observations can be made which provide a higher degree of certainty regarding the information obtained when compared to audio communications. By analysing this scenario, we observe the following:

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 the misinterpretation. Visual observation has the most significant effect and plays a major role in repairing loss of CG. This can be seen towards the end in the original case when the two aircraft have a view of each other, eight 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 they can see the aircraft in real time (also 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 that the loss of CG resulting from a coordination breakdown-e.g., due to factors identified by (Bearman et al., 2010) (Section 2.7), such as miscommunication or instrument malfunction-would not have led to the collision had visibility conditions been good. This observation underscores how a small change in contextual conditions can fundamentally alter our interpretation of events: actions previously perceived as "human error" or "root causes" instead appear as routine, everyday human behaviour in a different operational context.

#### 5.2.2. Variation 2: ATCo has a ground radar equipment

In this case it is expected that, with the help of the ground radar equipment, ATCo will notice when the PA aircraft fails to exit on the instructed C3 taxiway. This will most likely make the controller 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 using the ground radar, the ATCo notices the KLM aircraft performing a takeoff roll, and it is very unlikely that anything can be done to stop the aircraft at that point in time or to avoid the collision. The applied coordination mechanisms (D6, D7, R3) work as expected in this variation of the case too. While ATCo has a visual aid and knows about the crews' positions at all times when the visibility is low, the crews still have less than $500m$ of visibility. Hence, this scenario depends heavily on ATCo and their communications. By analysis of this scenario, the following observations were made:

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. We also cannot be sure if the ATCo would choose to ask KLM to abort first or to instruct PA to leave the runway ASAP. This choice could lead to unprecedented events, however within the time frame available to the agents in this case, the chance of impact stays high.
3. The presence of the ground radar did not necessarily prevent the impact from occurring. The coordination mechanisms, on the other hand, continue to play an important role. Having a ground radar does not ensure that ATCo will notice the agents' movements, and therefore the use of coordination mechanisms adds a necessary layer of redundancy.
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 ATCo can update their 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 single-runway 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 efficiency which could have played a part in avoiding the accident that day.
5. Less communication leads to less miscommunication. Communication can be and is lessened by the use to technology (radars, ADS-B etc.), however, less communication (or less miscommunication) does not necessarily lead to intended outcomes. While technology can help, the ability of the agents to communicate effectively (specially crucial state properties and higher-order plans/goals) stays crucial to efficient and safe operations.

### 5.3. Insights

We used agent-based simulation to perform predictive "what-if" analysis to explore the effects of the employed coordination mechanisms under different environmental conditions, such as good visibility and the availability of radar equipment. Based on this analysis, we concluded the following:

- Visibility conditions play an essential role in determining which coordination mechanisms are necessary to maintain CG between agents. In the scenario variation with good visibility conditions, by performing only visual observation the agents were able to identify and repair many losses of CG. However, the coordination mechanisms D6 and D7 introduced in the paper were still useful to quickly identify and repair CG losses, when non-standard terminology was used or radio communication was disturbed, as in the original scenario. Moreover, unsolicited repetition of crucial parts of the plans by ATCo (mechanism R3) helped maintain the CG regarding future intents of the agents that were not yet realized through actions. This was particularly useful in the investigated case study, in which agents formed inconsistent intents several times.
- Providing ATCo with a ground radar in the second scenario variation indeed decreased the need for communication about crews' positions at all times. Using radar information, ATCo could update their CG concerning the position states of the aircraft in a timely manner and form further plans to guide them. However, the presence of ground radar would not necessarily prevent the accident from occurring. The coordination mechanisms D6, D7 and R3 were still useful for identifying and repairing CG losses, similarly to the first scenario variation and would help preventing the impact between the aircraft.

## 6. Lessons learnt and contributions

In this paper, we formalized coordination using both theoretical frameworks and agent-based techniques (Section 4.4). We analyzed how common ground is established, maintained, lost and repaired by agents throughout the case study using the CVR transcripts (Section 4.5). We identified important mechanisms pertaining to CG loss and its subsequent repair (Section 4.6), and checked their usefulness and validity via a variability analysis (Section 5.2). Our study highlights the importance of coordination mechanisms in high-risk operational scenarios such as aviation operations, specifically in order to maintain common ground (CG) among agents. Based on the modelling and analysis of our selected case, we present the following conclusive remarks pertaining to coordination mechanisms and CG:

- It was observed that the CG between agents was lost undetected multiple times, even pertaining to crucial states, but is also recovered soon enough. These losses were usually not detected, but are repaired because of coordination mechanisms that are being used by the agents. These coordination mechanisms range from day-to-day rules of communication to protocol-based actions. Hence, CG loss need not be identified for it to be repaired. The coordination mechanisms act as safeguards (like unsolicited repeat of a crucial instruction) and repair the CG loss even without agents 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 need resolving. This cannot be simply done by adding automation as it does not account for the unknown unknowns. Hence, supporting human-human and human-machine coordination is important.
- Although many coordination mechanisms have been identified with various functionalities, none of them can be fully relied on to overcome even one kind of CG loss. This is because of the unpredictability inherent to sociotechnical systems. A better understanding of coordination can lead to improved reliability.
- 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. Coordination breakdowns occur when the agent is unaware of this loss and does not realise this unless the breakdown presents itself in the physical world (like an alert or notification from another agent). The agents usually lose common ground regarding the states of other agents by incorrectly 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.
- 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 occurs, for example, if the agents know the same plan but interpret it differently without even realising that their interpretations are different, namely a difference in stance S.
- Human memory plays an important role in all human coordination. Coordination breakdowns occur when people simply forget a step.

*Contributions.* The main contributions of our study are:

1. Three theoretical coordination modelling frameworks were integrated in a synergistic manner, obtaining a richer, formalized representation of coordination patterns and mechanisms, with a main focus on common ground. Detailed cognitive modelling of agents structured in coordination phases performed using these framework allows identifying specific cognitive states and relations that contribute to the generation of undesirable system states. In particular, the Co-ladder model (Chow et al., 2000) can be used to identify missing and faulty causal relations between states in relational patterns of communication and coordination in retrospective analysis of accidents and incidents.
2. The notion of common ground (CG) is formally defined and elaborated by a set of specific MASA relations for continuous, discrete, and intent states. These relations are particularly useful for a structured, retrospective analysis of incidents and accidents in safety critical organizations. The formal framework introduced in the paper (Table 6) allows identifying possible preconditions of these safety events, and to trace the dynamics of their propagation through the system in a systematic manner (Table 7). Based on our analysis, we proposed 10 generic mechanisms for identifying CG losses (Table 8), and six generic mechanisms for repairing CG losses (Table 10), as well as specific types of mechanisms for the crews and ATCos. To perform such an analysis for other use cases, one could follow the same methodological steps, as described in the paper.
3. The proposed modelling framework can also be used prospectively, in simulations of possible safety hazard scenarios and in real-time, real-life applications, to timely identify losses in common ground and propose mechanisms to repair them. To this end, one would need to define the formal MASA relations that need to be maintained, using the methodology of the paper. Then, based on observation and communication events of different actors, the applicable generic MASA update defined in the MASA modelling framework can be triggered to update agents' internal states and the corresponding MASA relations. An automated software agent can be implemented to actively monitor the MASA relations to timely identify (possible) inconsistencies and propose means to repair them, using the common ground identification and repair mechanisms proposed in this paper. The LEADSTO simulation language and the tool[6] can be used to automate such analysis.
4. The elements of common ground were systematically identified and formalized at three levels of awareness that are relevant not only for the case study considered in the paper, but also for the most of the ATM applications. These elements help the actors to be actively predictable to each other. Creating awareness of these elements and means to actively monitor them could be incorporated in the training of air traffic controllers and pilots.
5. The formal modelling and analysis of the use case and its variations show that access to additional observation modalities (e.g., ground radar) does not necessarily improve decision-making. Rather, the effectiveness of such observations depends on their alignment with the coordination mechanisms, such as those introduced in this paper. The role of these coordination mechanisms is innately crucial and should not be overlooked.

## 7. Conclusion

Modelling of the Tenerife accident is largely based on general protocols and interactions established in the area of air traffic control, which would be used in other cases too. Moreover, to define different types of losses of common ground we also used the list of categories of coordination breakdowns and their causes by (Bearman et al., 2010), which was synthesized over a broad range of ATM safety events. The losses of common ground in the case of Tenerife accident can be well placed in this list. In line with the modern Safety-II view (Hollnagel et al., 2015), 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 experienced agents sharing the same higher-order goals faced a coordination breakdown ultimately leading to a disaster. While external factors such a weather conditions and mental stress played a role, these can be considered part of normal conditions that agents face often during operations. However, on this day the outcome was deadly. This highlights both the emergent nature of sociotechnical systems and the need to better understand and support the human factor.
- With the help of simulations it was found 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 form the very basis of coordination.
- There are crucial states regarding which agents must, at all times, maintain common ground. These crucial states were identified in Section 4.6. 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, autopilot systems are trusted to handle routine tasks such as cruise control, while human operators retain the ability to take over when conditions deviate from normal operation. While this approach is understandable, it is also open to question. Humans may be more creative and intuitive than machines, but they are also prone to fatigue, stress, and misjudgment. As a result, neither humans nor machines are sufficient on their own. Instead, effective coordination between them offers the best chance of handling complex situations, highlighting the need to better understand human–machine interaction.
- Trying to identify root causes of accidents leads to endless speculation. For example, if the KLM aircraft had not fully refuelled then they might have lifted off over the PA aircraft or if the visibility conditions were good then the KLM captain would not have initiated takeoff, etc. Accident analyses therefore must move away from finding root causes but instead focus on the coordination dynamics that underlie individual events.
- Once the context is changed, the previously significant "human errors" in the case study seem to be reduced to normal human

[6] Available at: https://www.few.vu.nl/~wai/TTL/ Alternatively, a stable version is available via the Internet Archive at: https://web.archive.org/web/20240421152738/https://www.few.vu.nl/~wai/TTL/

behaviour. This demonstrates that there are no errors, but a partially understood human interaction. This underscores the need to better understand the human factors of safety-critical aviation operations.

### 7.1. Recommendations - ATM safety

Based on the findings of the analysis of the accident study, we present recommendations to support agents in sustaining, updating, monitoring and repairing common ground during coordination. These recommendations are predominantly aimed at the air traffic and management sector with the purpose to contributing towards safe operations.

1. Agents should be made aware of 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 a crucial state, 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 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. However, this recommendation 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 assumed that they are cleared for takeoff.
3. It is crucial for agents or teams to 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**. Two agents might be following the same plan with different interpretations without having any awareness or expectation of their interpretations being different. It is then difficult to realise what one does not know but must know. Hence, it is important to continuously ensure common ground by engaging with other agents.
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 the 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 several 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 can ensure that the CG is updated.
   - Because humans tend to forget, 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.

### 7.2. Future work

1. It is important to study ATM safety with the Safety-II view and also approach the complex ATM systems as sociotechnical systems. Defining safety by the absence of accidents creates a limited understanding of it. To describe safety scientifically, we must understand how people perform successful actions everyday and explain safety with the relevant evidence.
2. It is increasingly important to incorporate knowledge from psychological and social science in order to understand sociotechnical systems and when modelling coordination.
3. Comparative studies between models of coordination of an ATM hazard vs. regular operations would provide interesting insights into the underlying coordination mechanisms.

## CRediT authorship contribution statement

**Mannat Kaur:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis; **Alexei Sharpanskykh:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This article is based on research conducted as part of the first author's MSc thesis at TU Delft Causes, identification and repair of loss of common ground in coordination in ATM (air traffic management) Kaur, Mannat, TU Delft Master's thesis, 2017.

## Data availability

Coordination model is based on publicly available CVR transcript (cited in article). Complete versions of Tables 6 and 7 from the article are supplemented. LEADSTO source code has been made available.

## Appendix A. The elements identified based on the co-ladder model of communication and coordination

Tables A.15, A.18 and A.20

**Table A.14**
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 |

**Table A.15**
Plans.

| Term | Agent | Description |
|---|---|---|
| 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. |

**Table A.16**
Activities.

| Term | Agent | Description |
|---|---|---|
| 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.ε |
| 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 degrees 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." |

**Table A.17**
Expectations.

| Term | Agent | Description |
|---|---|---|
| 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- | 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. |

**Table A.18**
Events.

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

**Table A.19**
Analysis elements.

| TERM | AGENT | Description |
|---|---|---|
| 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 P9 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. |

**Table A.20**
Stance.

| TERM | AGENT | Description |
|---|---|---|
| S1 | KLM-CREW | Realize that PA is still on the runway. |

## Appendix B. Elements identified based on the MASA model

**Table B.21**
Discrete 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 | |

**Table B.22**
Intent 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, $td + s$) |

## References


Airline Pilots Association (APA), Human Factors Report on the Tenerife Accident, (1977), https://web.archive.org/web/20240524170543/, https://skybrary.aero/human-factors-report-tenerife-accident.

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

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

Bolton, R., Logan, C., & Gittell, J. H. (2021). Revisiting relational coordination: A systematic review. *The Journal of Applied Behavioral Science*, *57*(3), 290–322.

Bosse, T., Jonker, C. M., Van Der Meij, L., & Treur, J. (2005). Leadsto: A language and environment for analysis of dynamics by simulation. In *German conference on multiagent system technologies* (pp. 165–178). Springer.

Chow, R., Christoffersen, K., & Woods, D. D. (2000). A model of communication in support of distributed anomaly response and replanning. In *Proceedings of the human factors and ergonomics society annual meeting* (pp. 34–37). SAGE Publications Sage CA: Los Angeles, CA (*vol. 44*).

Clark, H. H., & Brennan, S. E. (1991). Grounding in communication. *Perspectives on Socially Shared Cognition*, (pp. 127–149).

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors*, *37*(1), 32–64.

Espinosa, J. A., Lerch, F. J., & Kraut, R. E. (2004). Explicit versus implicit coordination mechanisms and task dependencies: One size does not fit all. *Team Cognition: Understanding the Factors that Drive Process and Performance*, (pp. 107–129).

Government of Spain - Comisión de Investigación de Accidentes e Incidentes de Aviación Civil, Joint Report KLM-PAA, (1978), https://web.archive.org/web/20240524171057/, https://huntlibrary.erau.edu/collections/aerospace-and-aviation-reports/non-ntsb.

Ginzburg, J., & Fernández, R. (2010). Computational models of dialogue. *The Handbook of Computational Linguistics and Natural Language Processing*, (pp. 429–481).

Grimm, V., Railsback, S. F., Vincenot, C. E., Berger, U., Gallagher, C., DeAngelis, D. L., Edmonds, B., Ge, J., Giske, J., Groeneveld, J. et al. (2020). The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism. *Journal of Artificial Societies and Social Simulation*, *23*(2).

Grote, G., Zala-Mezö, E., & Grommes, P. (2004). The effects of different forms of coordination on coping with workload. *Group Interaction in High Risk Environments*, (pp. 39–54).

Hollnagel, E., Wears, R. L., & Braithwaite, J. (2015). From Safety-I to Safety-II: A white paper. *The Resilient Health Care Net: Published Simultaneously by the University of Southern Denmark, University of Florida, USA, and Macquarie University, Australia*, .

Jamroga, W., & Penczek, W. (2012). Specification and Verification of Multi-Agent Systems. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-31485-8-6

Klein, G., Feltovich, P. J., Bradshaw, J. M., & Woods, D. D. (2005). Common ground and coordination in joint activity. *Organizational Simulation*, *53*, 139–184.

Krock, L. (2006). PBS. https://web.archive.org/save/, https://www.pbs.org/wgbh/nova/article/final-eight-minutes/.

Malone, T. W., & Crowston, K. (1990). What is coordination theory and how can it help design cooperative work systems? In *Proceedings of the 1990 ACM conference on computer-supported cooperative work* (pp. 357–370).

Mintzberg, H. (1989). The structuring of organizations. In *Readings in strategic management* (pp. 322–352). Springer.

Sieck, W. R., Klein, G., Peluso, D. A., Smith, J. L., Harris-Thompson, D., & Gade, P. A. (2007). FOCUS: A model of sensemaking. Technical Report Klein Associates Inc Fairborn OH.

Weick, K. E. (1995). Sensemaking in organizations (vol. 3). Sage.