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Airport Complex System: Multifaceted Analysis With Extended Study On Accident Investigation

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Abstract

Airports are critical infrastructures playing a fundamental role in global connectivity by facilitating the transportation of passengers and cargo on an international scale. However, beneath the apparent simplicity of arrivals and departures, airports function as complex systems comprising a myriad of interdependent and interconnected elements. This article delves into the intricate nature of airports, emphasizing their distinctive features and associated challenges. In recent decades, the study of complex systems and various approaches to mitigate errors and prevent aviation accidents has gained prominence. Consequently, this work is developed to initially analyze the airport as a complex system and elucidating its defining characteristics. Subsequently, it explores ways in which these systems can be analyzed and managed to enhance overall safety and reliability. The core of this article concerns that some systems are designed without adhering to sound human-centered and human factors design principles can lead to situations where operator error becomes virtually inevitable, with accidents often being attributed to operator failure rather than system design flaws.

Keywords: accidents, airport, complex system, systems theory, AcciMap, CAST/STAMP

1. Introduction

This article proposes an analysis of airport operations from the perspective of Systems Theory. Initially, the authors' intention was to examine an international airport complexity by using a real aviation accident and apply the correlated accident investigation tools. Whilst collecting useful reports and mapping the contributing factors, we felt it necessary to give more attention to the concepts of complex systems and complex sociotechnical systems. In this sense, we sought to characterize an international airport as a complex sociotechnical system.

To adequately test this hypothesis, we created a simulated expansion of the original accident scenario, maintaining its plausibility, and modeled it with Causal Analysis based on Systems Theory – CAST (Leveson, 2019). Accident analysis was carried out using AcciMap (Svedung & Rasmussen, 2002). Our main assumption is that it is crucial to explore diverse perspectives when examining accidents in complex sociotechnical systems to seek more effective prevention strategies.

Introducing additional variables to the original event aims to analyze and test the insights that different accident models can provide. It is observed that specialized literature often employs real accidents to model and identify the lack of control or component failures leading to losses. Instead of opposing this approach, this article adopts it, incorporating additional events that may heighten concerns for prevention specialists when analyzing undesirable events.

The approach taken in this article begins with the definition of a system, followed by the characterization of a complex system, culminating in the presentation of airport operations as a complex sociotechnical system. The research conducted focuses on a real runway excursion accident at an international airport in northern Brazil. Furthermore, an event is introduced that could normally occur at the departure airport, located in southeastern Brazil, for example. The airport system is modeled using CAST, and the proposed accident and its variation will be assessed by the AcciMap.

1. Systems: a brief contextualization

Perfect systems do not exist in nature. Instead, systems are human abstractions and intellectual constructions to better understand events in a scientific manner. Early 17th-century philosophers understood systems as a sum of parts of an observable event, like Rene Descartes' android daughters (Kang, 2016), for instance, with his "automata" or "self-moving things" (Fig. 1), emphasizing the mechanistic view of entities or systems as self-moving machines. Hence, "simplicity", "stability" and "objectivity" were the premises to look at the events by a reduction process of their complexity and then to postulate function laws. These are the basis of traditional science.

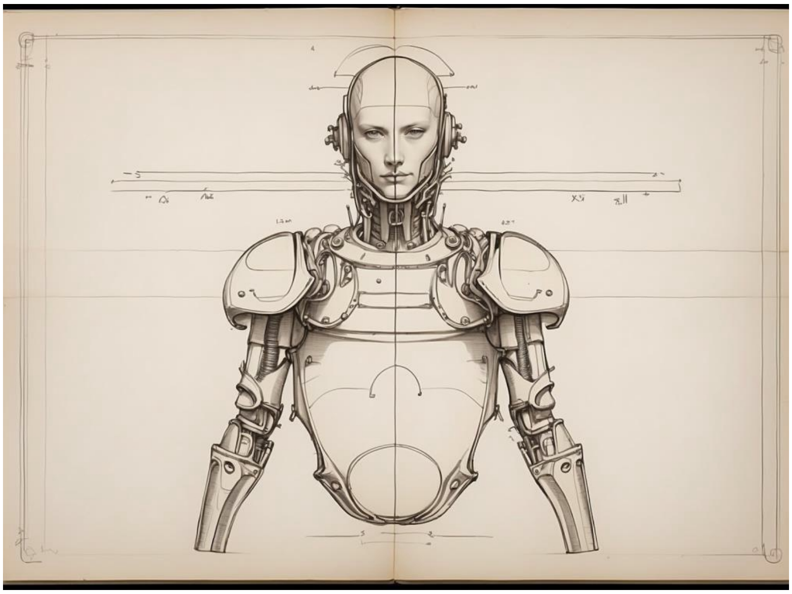

Fig. 1: An AI interpretation of a 17th century automaton representation.

In the 20th century, systems began to be approached in a holistic manner. Organizational theorist Russell L. Ackoff highlights that the trend of studying systems as an entity, rather than merely a collection of parts, aligns with the contemporary approach of science. This no longer seeks to isolate phenomena in narrow contexts but instead aims to open up interactions for examination and explore ever larger slices of nature (Ackoff, 1959 apud Bertalanffy, 1968).

Systems represent the most effective approach to understanding events and grasping their complexity, primarily defined as interconnected sets of elements organized cohesively to achieve specific objectives. This understanding, adopted for the purposes of this article, emphasizes three fundamental elements that characterize a system: individual elements, their interconnections, and an underlying purpose or function (Meadows, 2008). This perspective acknowledges that a system transcends the simple sum of its parts, highlighting the significance of relationships among elements and the orientation toward a common objective.

That said, the next step in our research was to model the basic functions of the airport. Our expectation was that Systems Dynamics concepts could provide more neutral airport knowledge than the traditional sense related to passenger processing. Thus, Figure 2 shows a graphical representation of a generic airport based on the stock and flow model and shows us a highly basic structure as a starting point. Considering the scope of the article, it is not appropriate at this time to go deeper and unfold the basic structure graph. Likewise, there is still no key point in our arguments to be analyzed using the concepts of system dynamics. However, this deeper treatment could be the subject of more specific research in the future.

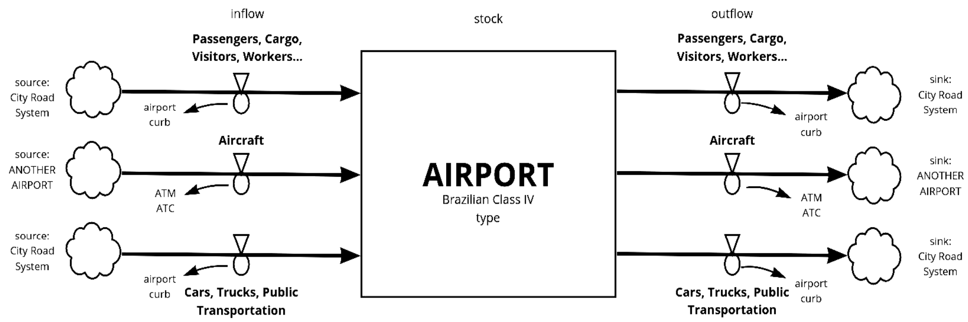

Fig. 2: Authors' depiction of an airport as a stock with multiple flows and inflows, based on Meadows (2008).

Systems are an intellectual construct, and the researcher can limit them to a preferred focus and level of analysis. Charles Perrow, a renowned sociologist known for his contributions to the analysis of complex systems, proposes a categorization of these systems into four levels, each representing distinct levels of aggregation between their components: units, parts, subsystems, and systems (Perrow, 1984). Perrow distinguishes between linear interactions and complex interactions to illustrate the dynamics present in systems. Linear interactions are those production or maintenance sequences that are expected and familiar, and those that are highly visible, even if unplanned. Complex interactions are those of unknown sequences, or unplanned or unexpected sequences, and not visible or not immediately understandable (Perrow, 1984). In the 2000s, Erik Hollnagel will develop more on this concept and we will look at it briefly below.

2. Airport as a complex system

An airport is, by the previous definition, a system. Nevertheless, an airport is also a part of a larger system, i.e., the air transportation system. Airports usually intermediate air operations and provide that a displacement for people and for cargo be effective. Since its beginning, the planning of an airport is such a complex process that the analysis of one activity without regard to the effect on other activities will not provide acceptable solutions. An airport encompasses a wide range of activities which have different and often conflicting requirements. Yet they are interdependent so that a single activity may limit the capacity of the entire complex (Horonjeff et all, 2010).

Additionally, the different components of an airport are highly interdependent. Changes in one area, such as runway delays, can impact the entire airport system, including the arrival and departure schedules, terminal capacity, and overall efficiency. This complexity can result in human behaviors that, under certain conditions, present security risks and, furthermore, there are concerns that some systems are designed without adhering to sound human-centered and human factors design principles. (Leveson, 2019). This lack of consideration can lead to situations where operator error becomes virtually inevitable, with accidents often being attributed to operator failure rather than system design flaws, and that is the core of this article.

Furthermore, complex sociotechnical systems are unpredictable, variable and they must be designed to absorb, adapt, and recover from disruptions, not just to avoid failures. Also, for Perrow (1984) and Hollnagel (2012), systems can be seen as tractable or intractable (Fig. 3).

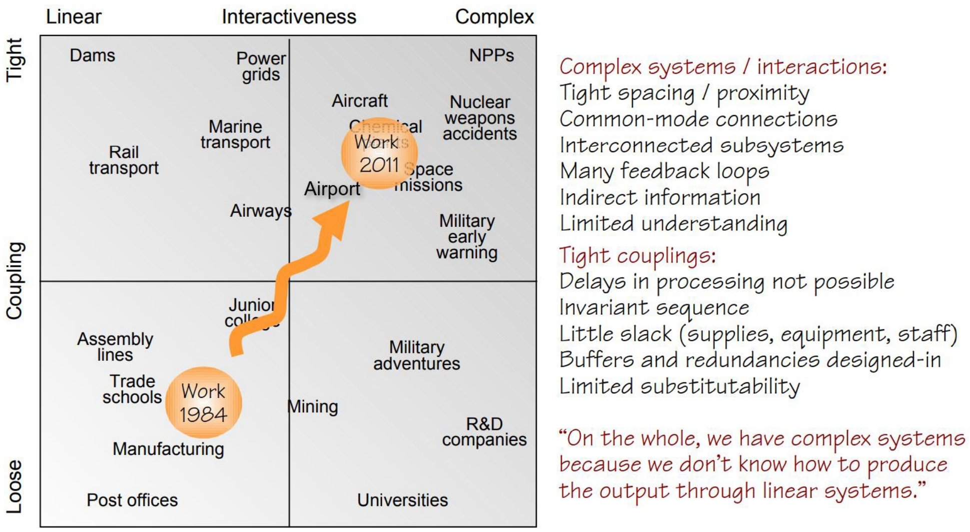

Fig. 3: Hollnagel's view about the evolution of the tractable and intractable systems over Perrow's graphical approach.

We assume that airport belongs to the second quadrant in the Hollnagel's figure above due to the diversity of tight coupled components interacting in a complex manner. These components include runways, terminals, air traffic control systems, security services, and baggage areas, among others. Each component has distinct functions and interacts in intricate ways. Additionally, the different components of an airport are highly interdependent. Changes in one area, such as runway delays, can impact the entire airport system, including the arrival and departure schedules, terminal capacity, and overall efficiency (Horonjeff et all, 2010).

Besides, the extensive use of advanced technology, including automation systems, aircraft tracking, safety and security systems, and sophisticated communications, further contributes to the complexity of the airport environment. The high volume of passengers, baggage, cargo, and aircraft moving simultaneously through international airports poses significant logistical challenges, requiring careful management to promote efficiency and safety (Horonjeff et all, 2010).

Additionally, safety and security regulations play important roles in airport operations. Safety and security matters are considered top priority at airports. They necessitated a high-level concern from ramp workers and aviation crews, a complex surveillance, control, and emergency response systems, and prepared C-level executives. Additionally, airports must continuously manage and comply with strict regulations. That said, the complexity of airport systems necessitates an integrated and coordinated approach to guarantee secure and efficient operations, owing to the combination of these factors.

For a system to be controllable, it is necessary to know what is happening inside it. More specifically, it is necessary to have a sufficiently clear description or specification of the system and its operation (Hollnagel, 2012). The same requirement must be met when a system is analyzed, for example in risk assessment. Thus, maintaining the concepts of Systems Theory, the authors decided to map a generic airport using the STAMP - System-Theoretic Accident Model and Processes toolbox, developed by Nancy Leveson at the MIT – Massachusetts Institute of Technology.

4. Mapping the airport system: frameworks available

Whilst presenting systems in item 2, we have seen that traditional decision theory research perceives decisions as discrete processes that can be separated from the context and studied as an isolated phenomenon. More recent research has taken a quite different approach: Instead of thinking of operations as predefined sequences of actions, human interaction with a system is increasingly being a continuous control task in which separate "decisions" or errors are difficult to identify (Leveson, 2004).

Given the recognition of the power of the systems approach, the authors were firmly inclined to choose frameworks that dealt with complex sociotechnical systems rather than the traditional analytical approach like

Fault Tree Analysis - FTA, Event Sequence Diagram - ESD, Event Tree Analysis - ETA, FMEA/FMECA, Hazop/LOPA, What-if/Checklist, brainstorming, Preliminary Hazard Analysis, Delphi, ranking tools like TOPSIS, Vikor in some way. Fig. 4 depicts three ways of understandig the causality of accidents (Hollnagel, 2012).

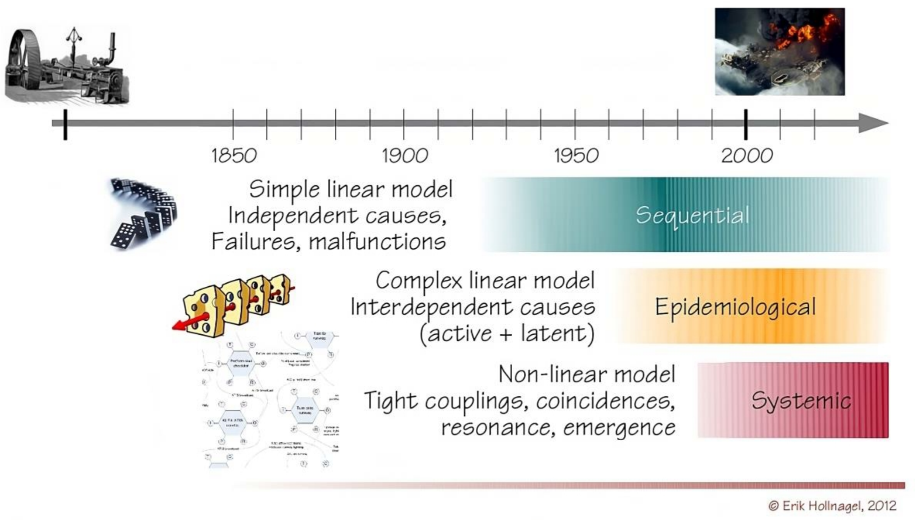

Fig. 4. three ways of understandig the causality of accidents (Hollnagel, 2012).

We found a study from (Cardoso Jr, 2020) that shows a framework that identifies four system categories: Chaotic, Complex, Complicated and Simple. The Cynefin framework, a Welsh word that means the multiple, intertwined factors in our environment and our experience that influence us (how we think, interpret and act) in ways we can never fully understand. For the Complex category, Cynefin points that methods and tools like System Dynamics, Agent-Based modelling, Functional Resonance Analysis Method - FRAM and Systematic-Theoretic Process Analysis - STAMP/STPA are suitable to face the challenges imposed (Cardoso Jr, 2020).

Another recent study by (Borges and al, 2022) developed a risk analysis framework for complex aerospace research projects by integrating different methods: problem structuring, safety control action analysis, and prioritization of results. Although there were some considerations to take into account, (Borges and al, 2022) found that from all the methods that were evaluated to identify a higher number of potential causes to prevent accidents in complex systems, STAMP and its derivative technique for hazard analysis, the Systems-Theoretic Process Analysis (STPA), received considerable notoriety.

The authors strive efforts to avoid the many limitations in the way accident causal analysis, five of them likely to be the most important, according to LEVESON (2019): root cause seduction and oversimplification of causal explanations, hindsight bias, superficial treatment of human error, a focus on blame, and the use of models of causality that do not fit today's world.

STAMP is a model or set of assumptions about how accidents occur, and an alternative to the chain-of-failure-events or dominos or Swiss cheese slices, all of which are essentially equivalent (Leveson, Thomas, 2018), that underlies the traditional safety analysis techniques. STAMP integrates into engineering analysis the causal factors in our increasingly complex systems such as software, human-decision making and human factors, new technology, social and organizational design, and safety culture (Leveson, 2019). STPA is a powerful new hazard/cybersecurity analysis technique based on STAMP while CAST - Causal Analysis based on System. Theory - is the equivalent for accident/incident analysis.

CAST, along with Jens Rasmussen's AcciMap, is a based Systems Theory causal analysis approach that assists in identifying only the particular scenario that an accident occurred. The main understanding at this point is that past accidents analysis is significant to apply hazard analysis tool to identify plausible scenarios that need to be eliminated or controlled to prevent further losses (Leveson, 2019).

AcciMap is based on the principle that behavior, safety, and accidents are emergent properties of complex sociotechnical systems. These emergent properties are created by the decisions and actions of all stakeholders within a system – politicians, chief executives, managers, safety officers, and work planners – not just by front line workers alone (Cassano-Piche, 2009). Safety is therefore the shared responsibility of all actors within a particular system, and accidents regardless of size or consequence are created by the interacting decisions and actions of multiple actors across the system. AcciMap having been used to analyze accidents from contamination of drinking water, severe acute respiratory syndrome outbrake, gas plant, train crash, to aircraft accidents, among others (Branford, 2009).

The safety control structure enforces the safety constraints. Responsibility for enforcing specific behavior on the system is distributed throughout the system's control structure (Leveson, 2019). According to the premises that underlie in CAST approach, accidents result from inadequate enforcement of the system safety constraints in the operation of the system as a whole. In other words, weaknesses in the safety control structure leads to violation of system safety constraints and thus losses (Leveson, 2019). Fig 4 below presents a model of the sociotechnical control structure frequently seen in airports based on STPA/CAST.

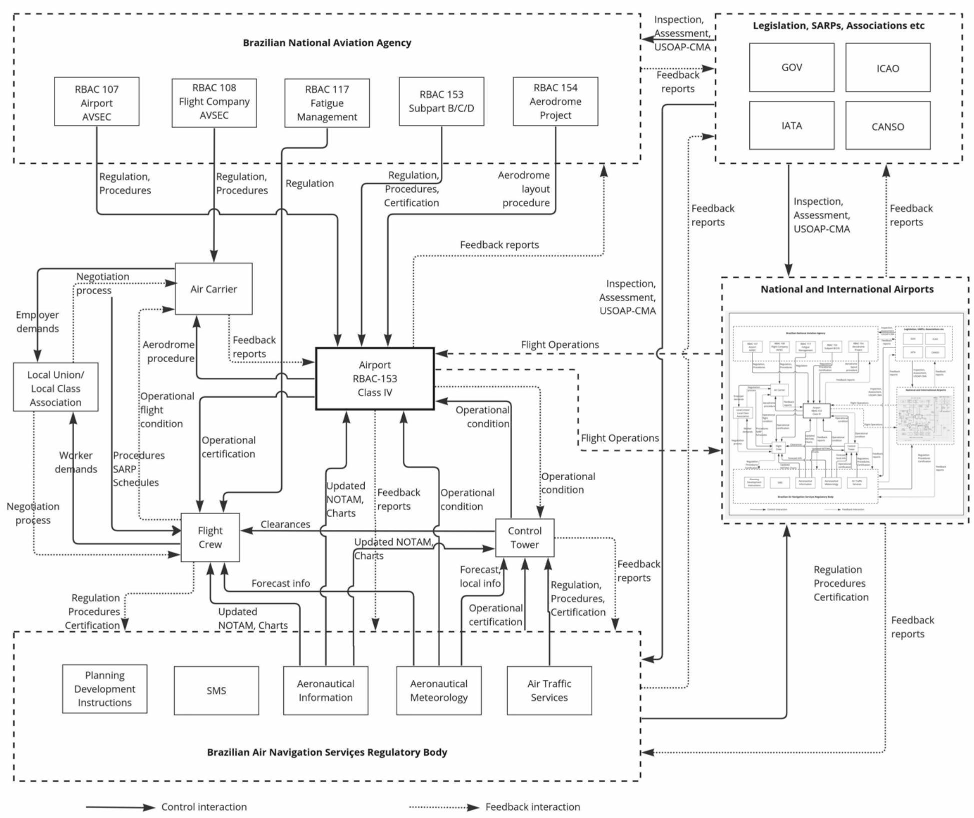

Fig. 5. General international airports safety control structure based on STPA/CAST – a Brazilian sample (authors' perspective).

5. The accident of reference: a runway excursion

Primary threats to our survival, both of our organizations and of our societies, come not from sudden events but from slow, gradual processes; the arms race, environmental decay, the erosion of a society's public education system, increasingly obsolete physical capital, and decline in design or product quality (at least relative to competitors' quality) are all slow, gradual processes (Senge, 1994).

Managers often have trouble grasping the complexity and normality that gives rise to such large events. The growth of complexity in our organizations and their technologies has outpaced our understanding of how complex systems work and fail. Organizations do not just fail because of component breakage or linear propagations of breakdowns. Instead, failure breeds opportunistically, non-randomly, among the very structures designed to protect an organization from disaster.

A common pattern is a drift into disaster - a slow, incremental decline into bad judgment by organizations that take past results as a guarantee for continued success. These were systems that drifted into failure (Dekker, 2013). Runway overrun is a type of runway excursion in which the aircraft departs the end of the designated runway once it is unable to stop within the runway limit. In this article we will consider a runway overrun as the accident of reference (Reiser et all, 2022).

Runway excursions could happen both when an aircraft touches the ground too far away of the aiming point, which is usually 1,000 feet (305m) from the runway threshold or by an inadequate or late use of deceleration devices, such as ground spoilers, engine thrust reverser, normal or even emergency brakes. It can occur on takeoff or landing when an aircraft does not maintain at least one of the following variables stable - speed, descent rate, vertical/lateral flight path and in landing configuration, or receive a landing clearance by a certain altitude (Reiser et all, 2022).

In the Global Aviation Safety Plan (GASP), the International Civil Aviation Organization (ICAO) has identified five global high-risk categories of occurrences (G-HRCs) as global safety priorities in the 2023–2025 edition of the GASP: Controlled flight into terrain (CFIT); Loss of control in-flight (LOC-I); Mid-air collision (MAC); Runway excursion (RE); and Runway incursion (RI). The impact of the runway excursion on aviation operations worldwide is depicted in Fig. 5 comparing it with other common occurrence categories (ICAO, 2023a).

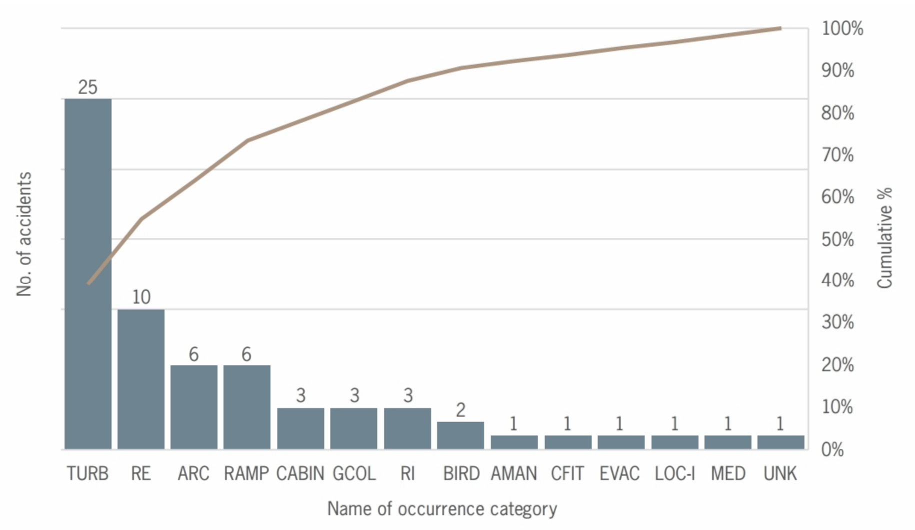

Fig. 6: Runway Excursion occurrences, among others. ICAO Safety Report | 2023 Edition (ICAO, 2023b)).

6. The final report and author's hypothesis

A passenger transport flight went on without any abnormality until its approach for landing on runway 29. On the surveillance radar, the aircraft performed its approach at 170kt (315km/h), and the investigation team observed that it was 20kt (37km/h) above the speed recommended in the aircraft Quick Reference Handbook (QRH). According to the final report, "it is possible that part of that speed was caused by the wind component, which, at that time, was approximately 5kt (10km/h) tail" (Brazil, 2021). Simultaneously, the Control Tower already had information of the changing prevailing wind then favorable for landing on runway 11. The air traffic control did not inform the crew about the tailwind, providing only the reading of the present wind.

The runway-change protocol was never started by the air traffic control, nor was the crew instructed to perform the circling procedure to runway 11, given the new direction of 180° with the intensity of 16kt (aprox. 30km/h). The final report found the tailwind landing resulted in an increase in the distance required to stop the aircraft. and the aircraft crossed the runway limits, coming to a full stop 100 metres (about 328.08 ft) after threshold 11, in soft terrain. The aircraft had minor damage. All the occupants were left unharmed. Brazilian aviation accident investigation board classified it as a runway excursion.

To better configure the complexity and level of tractability (Perrow, 1994, Hollnagel, 2012) of an airport as the system chosen for analysis, the authors decided to add to the reference accident a component in the scenario of a takeoff airport that would check the plausibility of occurrence for the same result.

Thus, the authors added to the investigated accident scenario a VIP class passenger (very important person) who was late for check-in at the boarding airport both because of city traffic and the access road to the airport curb boarding. This means that there are external forces of human origin acting and interfering in the natural entrances and exits of the airport, as seen in Fig. 2.

These entirely plausible events will have an impact on the aircraft's take-off and on the flight crew's legal working hours limit, contributing to a destabilized approach to the destination airport and consequent departure from the runway, as they seek to compensate for the delay still in flight.

7. AcciMap started analisys

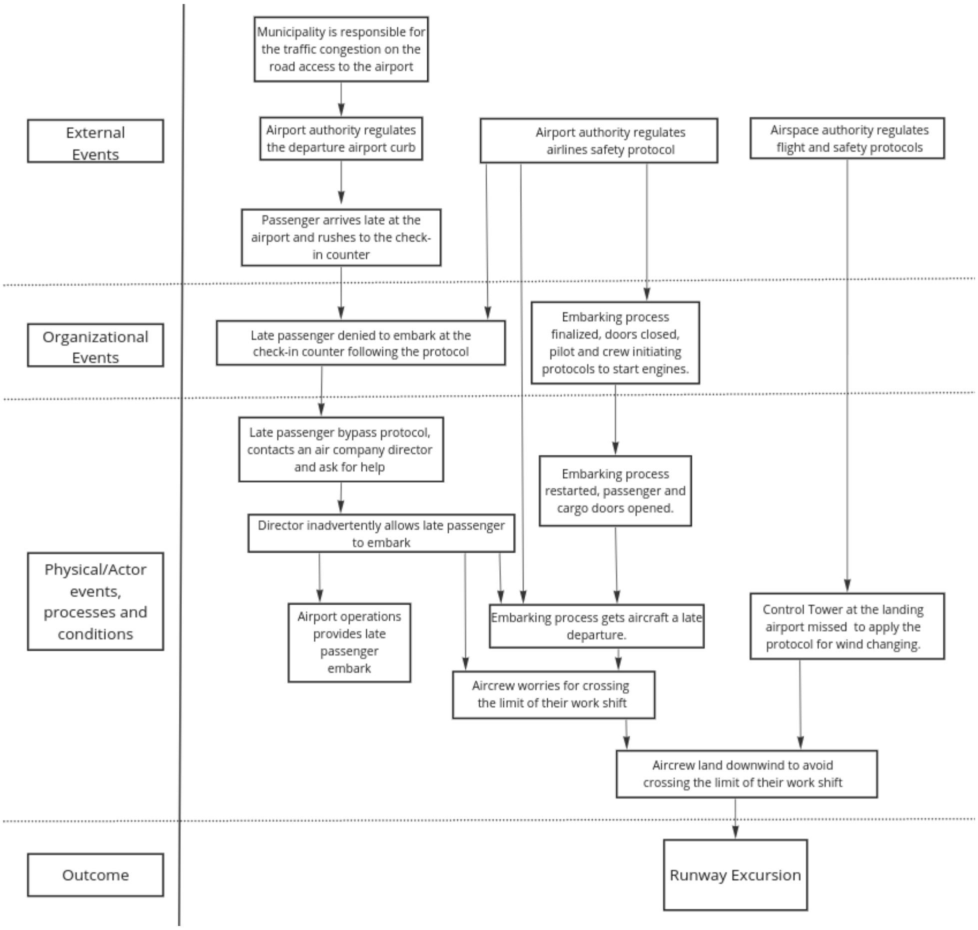

Fig. 7: Author’s started AcciMap analisys of the accident extended version.

8. Conclusion

By delving deeper into the complexities of airport operations, emphasizing their interconnected elements and potential vulnerabilities, the authors’ conclude that the approach using Systems Theory in accident causality analysis enables more successful identification and management of risks in complex sociotechnical systems and provides greater capacity for learning about the system itself.

Summary

Two different accident investigation models based on systems theory were used both to map the high-level control structure of a generic international airport and to identify the decisions and actions of the actors involved in a given accident. A small but significant modification was made to the chosen accident to evaluate more components of the airport. It allowed expanding the perspectives of its safety control structure.

The authors’ intention was to examine the final report and propose a broader exploration of the intricate nature of airports as complex socio-technical systems with a very plausible event at the departure airport of the aircraft missing the runway. CAST was chosen to map the airport's high-level security structure, while AcciMap was applied as an accident investigation tool The article proposes that this can happen either by investigating real occurrences as they are presented to the investigation team, or by adding hypothetical and plausible situations to happen in order to evaluate the weaknesses and strengths of the airport control system.

This article seeks to contribute to improving prevention and monitoring strategies by aligning with the state of the art in understanding the management of uncertainty and variability in complex systems.

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