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Using AcciMap As Systemic Analysis Tool

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Abstract

This study proposes the use of the Accident Mapping Method (AcciMap) from a fresh perspective, as a management support tool for systemic analyses. The idea put forth is that, during a comparative analysis of various AcciMap graphs collected from accidents/incidents sharing the same organizational links, the recurring and common elements/factors found in those graphs may indicate systemic failures. By observing the mapping of recurring and common elements/factors among the AcciMaps, stakeholders' involvements and responsibilities can be specified. Actions (direct or indirect) that may not have been previously identified or recognized as contributing elements/factors to increased risks in the overall framework become apparent. Illustratively, the study delves into the histories of two sounding rocket launch campaigns for microgravity experiments, Cumã (2002) and Cumã II (2006), within the Brazilian Space Agency's Microgravity Programme. These campaigns, involving VS-30 XV06 and VSB-30 V04 sounding rockets, address intricate sociotechnical systems. Each sounding rocket carries a microgravity platform responsible for housing scientific and technological experiments, supporting functions such as power supply and data communication (downlink/uplink). Additionally, it features a stabilization system (to establish the microgravity environment) and a parachute recovery system. Unfortunately, both launch campaigns were unsuccessful in retrieving their platforms from sea recovery.

Keywords: accimap, accidents, incidents, failure analysis, systemic analysis, management

1. Introduction

Aerospace projects play a fundamental role in modern society, providing not only many daily conveniences, but serving as a significant driver for technological innovations across diverse areas. However, these systems are characterised by a complex sociotechnical nature, blending human interactions, engineering, science, and technologies, and dealing with increasing risks and uncertainties.

Aerospace projects are typically characterised by advanced technology, various mission types, complex integrations between hardware and software systems, and inflexible time schedules dictated by "launch windows" (Sauser, 2005). In Brazil, particularly, space projects are subject to purchase restrictions, a lack of human and financial resources, international embargo policies, government policies, and the loss of capabilities of developing institutions (Corrêa, 2013).

Perrow (1984) subjectively categorised the organisational world, creating a matrix based on complexity and coupling (Figure 1), emphasising that space missions exhibit complex interactions and tight coupling. These missions represent systems naturally with an overly complex degree of interaction, with strong coupling indicating that:

- they have time-dependent processes: they cannot wait or delay until addressed.
- sequences are more invariant. B must follow A because that is the only way to manufacture the product.
- not only specific sequences are invariant, but the overall process design allows only one way to achieve the production goal.

- there is little slack. Quantities must be precise; resources cannot be substituted for each other; wasted supplies can overload the process; equipment failures cannot be tolerated. Weight and space are limited in space rockets, so redundancy is avoided. The high project cost is a limiting factor.

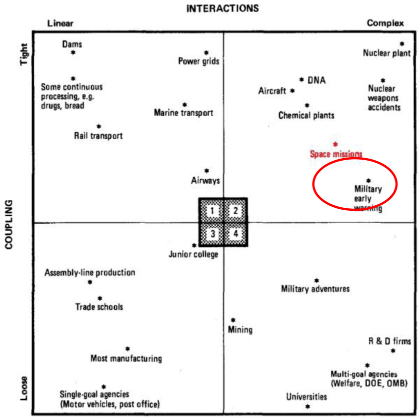


Fig. 1. Interaction/Coupling chart.
Source: PERROW, 1984. “Space Missions” item highlighted by the authors

Space missions involve the utilisation of four segments: *space segment* (payload and basic satellite body), *launcher segment* (sounding rockets and launchers), *ground segment* (command, control, communication, and tracking systems), and *user segment* (community using services or receiving generated data). These segments, alone or together, may experience incidents/accidents due to complexity and/or interactions, compromising the mission.

Over the years, various methods for incident/accident analysis have been developed, focused on specific niches according to the needs and characteristics of the study area. Once verified and validated, they have been incorporated into a toolkit available and widely usable by the scientific community. Some of these tools can be used for both incident/accident analysis (post-occurrence) and risk analysis (prevention). Indeed, a biunivocal relationship is established between these proactive and reactive views, leveraging the lessons learned, which promote the consolidation of knowledge over time and the change in risk perception.

Considering that revisiting incidents/accidents from the perspective of new methods involves a timeless process that promotes a re-examination in search of new evidence and learnings, we have Appicharla (2023), who recently analysed the accidents of the Space Shuttle Challenger (1986) and the Space Shuttle Columbia (2003). Appicharla suggests that "organisational and management factors, in the form of insufficient systems engineering, contributed to the disasters." Similarly, our case study proposes to reanalyse two specific incidents (Cumã/VS-30 XV06 Mission in 2002 and Cumã II/VSB-30 V04 Mission in 2006) complementarily to the analyses conducted by the respective accident/incident commissions, aiming to identify and understand the causal factors of the incidents/accidents, extract lessons learned, and strengthen the idea of using the AcciMap method as an additional basis for incident/accident analyses in flight.

The article is structured as follows: Section 2 presents a literature review. Section 3 provides a concept of weightlessness (or microgravity) and talks about sounding rockets for microgravity experiments and microgravity platforms. Section 4 characterises the Joint AcciMap Analysis (focus of this article), presenting its roadmap. Section 5 presents a report of the Cumã and Cumã II mission incidents, develops the missions' AcciMaps, and performs the final joint analysis. Section 6 presents the final conclusion of the study, highlighting the importance of the analysis conducted and proposing recommendations for future studies.

2. Literature review

2.1. Complexity

The theory of complexity provides an understanding of how systems grow, adapt, and evolve. According to Sammut-Bonnici (2014), the key characteristics of complex systems are:

- increasing returns: the concept rooted in economic and evolutionary theories, as well as complexity dynamics, explores positive feedback mechanisms, particularly evident in our understanding of economic, evolutionary, and complex systems, including the influence of network technologies;
- self-organizing systems: exemplified by phenomena like bird flocking and market dynamics, rely on subconscious rules guiding individual behaviour to create harmonious, emergent patterns without centralized control – a bottom-up process evident in complex systems such as economies and natural formations;
- continuous adaptation: illustrated in the stock market and various contexts like the global economy, online networks, and ecology, displays a dynamic feedback loop where behaviour modification in response to environmental changes leads to evolving and cooperative systems, as seen in the mobile telecommunications industry;
- sensitivity to initial conditions: exemplified by chaotic systems like the weather and described by the 'butterfly effect', leads to unpredictable scenarios in complex systems, as seen in investor reactions to critical events and threshold points in the stock market influenced by psychological factors;
- nonlinearity: in complex systems, exemplified in stock markets, emerges when the combined actions of interacting agents produce effects greater than the sum of individual parts, resulting in nonlinear behaviour such as bull and bear markets.

On the other hand, "Complexity" refers to a measure of the project scope reflected in characteristics such as the number of tasks and the degree of interdependence among them. As complexity increases, the number of components and the need for interactions and coordination also increase (Shenhar, 2010).

Simon (1996) defines a "complex system" as a system composed of many parts that interact in a non-simple manner. In such systems, the whole is more than the sum of its parts, not in an extreme metaphysical sense, but within the important pragmatic sense where, given the properties of the parts and the laws of interaction, it is not a trivial matter to infer the properties of the whole.

Hobday (2000), in turn, argues that the complexity of products can be characterized as a matter of degree. Several dimensions of product complexity are presented, including the number of components, the degree of customization of both systems and components, the number of design choices, the elaboration of system architectures, the scope, the depth of knowledge and skill required for implementation, and the variety of materials and information needed.

2.2. Accident Mapping Method (AcciMap)

The AcciMap (Accident Map Method) is an accident investigation method developed and proposed by Rasmussen. This can be considered the first method that considers the concepts of sociotechnical systems in industrial processes and the risks of serious accidents (FU et al., 2020). Sociotechnical systems are those that consider events with a significant influence of human factors, both in actions and decisions, which interact with the technological aspects involved in the process. In proposing AcciMap, Rasmussen presents a structured method composed of six layers: government; associations and regulators; company; management; advisory network (staff); workers (FU et al., 2020). Each layer presents the actors involved (whether institutions or functions), as well as the events related to the causes of accidents, interconnected by arrows as causality is established between them. The AcciMap model recognizes all actors at the forefront regarding conditions, decisions, and actions; their interrelationships and contributing factors. WIENEN et al. (2017) classify AcciMap as a type of Epidemiological Method, which is modelled around events but adds latent layers, i.e., pre-existing situations before the accident that were not recognized. According to the authors, the great advantage of this class is that it allows evaluating the sociotechnical context, thus highlighting possible failures in administration, corporate culture, safety procedures, deficiencies in legislation etc. Such characteristics are not observable in sequential methods. For this reason, these methods tend to take longer to conclude, as they require in-depth investigation. Moreover, they require all involved parties, especially those in higher layers, to be receptive to absorbing the lessons learned, as management process flaws are often identified, even indirectly. Qureshi (2008) emphasizes AcciMap's foundation on Rasmussen's risk management framework, using functional abstraction models to understand adaptable sociotechnical systems. These models illustrate information flow in hazardous process control systems. Rasmussen and Svedung recommend a phased accident analysis method, incorporating graphical representations. Core steps involve selecting and analysing accidents, identifying actors, creating a Generic AcciMap, and conducting work analysis.

3. Weightlessness (Microgravity) and Sounding Rocket Missions

3.1. Weightlessness (Microgravity). Concept

The force of gravity acts incessantly on the Earth's surface, directly influencing all the phenomena we know. The environment of weightlessness (or microgravity) is characterized by low gravitational acceleration, where gravitational forces have a reduced impact on the dynamics of observed scientific phenomena.

It serves as a unique laboratory for conducting scientific experiments, where the reduced influence of gravity leads to the absence of sedimentation, buoyancy, thermal convection, hydrostatic pressure, and condensation upon contact with containers (as liquid bridges can form).

In particular, the sounding rockets' weightlessness environment for conducting experiments is characterised by:

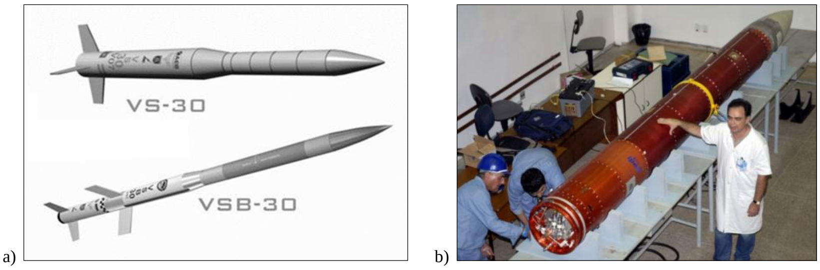
- low level of gravitational acceleration (reduction in gravitational acceleration);
- extremely low orthogonal angular velocities (reduction in centripetal accelerations);
- extremely low or non-existent internal vibrations (reduction in accelerations due to vibrations resulting from aerodynamic flow and propelled flight phase).

3.2. Sounding rockets and experiment platform

The VS-30 (single-stage) and VSB-30 (single-stage with booster) sounding rockets are produced by the Institute of Aeronautics and Space (IAE). As part of the Microgravity Programme of the Brazilian Space Agency (AEB), these rockets transport platforms for conducting experiments in a microgravity environment. The platforms for experiments in microgravity are responsible for protecting the experiments during flight, facilitating communication of experiment data and video to the ground, initiating the experiments in microgravity, and recovering the experiments in flight, safeguarding them from seawater. The one used for the VS-30 vehicle weighs about 200 kg and provides a microgravity environment of approx. 3 min, while the VSB-30 vehicle's platform, carrying more experiments and weighing about 400 kg, creates a microgravity environment of approx. 6 min.

In a mission, incidents are possible; everything is dynamic, interdependent, and basic systems lack redundancy due to the need for weight reduction in flight. Moreover, the atmospheric conditions at the launch site and the splashdown point, as well as the rescue operation itself, if not satisfactory, can also impact the mission.

Within an agreement with the German Aerospace Center (*Deutsches Zentrum für Luft- und Raumfahrt* – DLR) through its Mobile Rocket Base department ("*Mobile Raketenbasis*" – MORABA), which has a tradition in developing platforms for microgravity experiments in Europe, we obtained, through a barter, two platforms for use in the Microgravity Programme of AEB. One of these platforms, named MICROG1 (a platform based on the technology of the German TEXUS platform) was used in the Cumã II mission. The predecessor mission, Cumã, utilized a test platform called X1 (a platform based on the technology of the German Mini-TEXUS platform), smaller than MICROG1, owned by DLR/MORABA. The X1 platform was offered as a test to verify the suitability of the VS-30 rocket and later the VSB-30 rocket for Brazilian and European microgravity experiment missions. At the time of the Cumã mission, the VSB-30 vehicle was still in development. Its qualification flight (VSB-30 V01) took place in 2004. Figure 2 shows in a) the sounding rockets for experiments in a microgravity environment and in b) the experiment platform MICROG1 for conducting experiments with the VSB-30 sounding rocket.



Source: IAE

Source: *Agência Brasil*

Fig. 2. (a) Brazilian sounding rockets for microgravity platforms; (b) MICROG1 Platform (Op. Cumã II/2006).

4. Joint AcciMap analysis description

As previously mentioned, the idea is to conduct a comparison between AcciMaps of different accidents/incidents that share a common basic structure characterized by the same group of stakeholders, organizations, and nature. This involves gathering common and key elements/factors to assess and/or confirm the recurrence of issues that may indicate a problem or a systemic failure.

Each AcciMap has its specific elements/factors that may be common (recurrent) among different accidents/incidents, whether they are the main cause or not of the respective occurrences. The hypothesis is that as we progress through these structures, from bottom to top, a greater number of common (recurrent) elements/factors can be identified. Consequently, if not effectively managed, these systemic elements/factors may contribute to the perpetuation and expansion of an environment conducive to more occurrences.

4.1. Proposed analysis. Step-by-step

- 1st step: establish the levels and the actors for each AcciMap;
- 2nd step: create an AcciMap diagram for each accident/incident to be compared, avoiding bias/tendencies;
  Note: use similar terminology to describe AcciMap elements/factors, aiming to facilitate the identification of common elements/factors between distinct accidents/incidents.
- 3rd step: identify common elements/factors and specific elements of each accident/incident, highlighting the recurring occurrences (recurring elements/factors);
- 4th step: identify the main recurring elements/factors and the main specific elements/factors from elements/factors raised in each AcciMap according to previous step;
- 5th step: based on the organizations' profiles and the nature of the activities conducted, establish the criticality criteria to be used and analyse the recurring main elements/factors listed to identify critical recurring main elements/factors with potential for systemic failures. Identify the level at which they occur and, if possible, assess the available actions to reverse a future failure within your field of action;
- 6th step: Issue an alert reporting the observed systemic failure(s) to the responsible(s) stakeholder(s). Alert your organization and, if applicable, report to other actors found at other levels of the hierarchy structured into the AcciMap.

5. Case of Study

5.1. A brief report of the Cumã mission’s incident

According to AEB (2003), the launch operation of eight experiments from universities and research institutions aboard the German microgravity platform X1 (a test platform similar to the German Mini-TEXUS platforms) using the VS-30 XV06 sounding rocket took place on December 1, 2002, at the Alcântara Launch Center (CLA), Maranhão, Brazil. During ascent, the rocket and platform prematurely separated, resulting in a platform apogee of only 60 km, failing to achieve the required conditions for microgravity. The probable cause of the premature separation was the use by DLR/MORABA of a fixation element in the rocket/platform interface (motor adapter) designed for a different sounding rocket, potentially lacking the structural resistance required for the VS-30 flight regime. Another possibility for the premature separation could be incorrect torque of the manacle ring due to the use of an inappropriate torque wrench. The DLR/MORABA reported using a parachute with a float from a larger 400 kg capacity platform (TEXUS), causing the float to sink within the parachute during the initial reefing phase. As the lighter platform descended more slowly, not fully filling the area during the reefing phase, the reduced cross-sectional area increased the free-fall speed. When the parachute fully opened, it experienced a severe shock, tearing the parachute. The platform impacted the sea at approximately 80 m/s, breaking into pieces and sinking to a depth of 30m. The main parachute assembly was recovered. It was found that the seams of the recovered parachute lacked safety margins for nominal tensile forces for a TEXUS platform’s kind. The recovery system, as well as the motor adapter, was the responsibility of DLR/MORABA.

Another failure occurred in the radar tracking, which followed the motor's trajectory, not the platform's one, after premature separation. The radar designation was made visually and manually, with the CLA operator mistaking the motor for the platform and instructing the radar to track it. The motor flew stabilized, without the platform, to an altitude of 120 km. The platform's estimated impact point was determined later, guiding the searches conducted by the Brazilian Air Force (FAB). Table 1 provides a summary of the most relevant flight anomalies observed in this mission.

Table 1. Most relevant anomalies of the vehicle in flight.

Time (s)	Anomaly Description	Anomaly Causes	Consequence on Flight and Observations
L0+2	Variation in nominal elevation	High-speed surface wind.	Influence on the vehicle trajectory with variation in apogee and range.
L0+14	Roll resonance (duration of about 4 s).	Dynamic instability during flight.	▪ slight influence on trajectory; ▪ unexpected lateral accelerations (shock).
L0+25	Premature separation of the platform.	Unknown irregularity at the platform separation system.	Influence on the platform trajectory with reduced apogee and range.
L0+500	Irregularity in the main parachute system device.	▪ float selected heavier for the platform weight; ▪ parachute seams made with low safety margin.	▪ tear of the platform parachute; ▪ separation of the main parachute/float system from the platform with impact on the water; ▪ platform loss.

Note: L0 = *liftoff time*; Source: Adapted from AEB (2003) by the authors

5.2. A brief report of the Cumã II mission's incident

Multiple delays occurred in scheduling the Cumã II mission due to the development of the experiments by universities and the DLR/MORABA launch campaign schedule in Europe, leading to significant political strain between IAE, DLR/MORABA, and AEB. According to AEB (2008), the mission used the VSB-30 V04 vehicle, carrying the Germain-Brazilian MICROG1 platform and ten experiments for microgravity research from Brazilian universities and scientific institutions. It took place on July 19, 2007, reaching an apogee of 250 km, successfully establishing the microgravity environment for experiments. During the descent phase, an onboard camera filming the parachute system's opening indicated that the recovery system had been activated at 493 s of flight (approximately 19.3 km altitude), when it should have been activated at 611 s (approximately 4.8 km altitude). This premature opening destroyed the parachute, causing the platform to impact the sea at an extremely high speed, with no possibility of recovering the platform or the experiments. Figure 3 shows a photo with no parachute at 516.2 s into the flight, confirming that the main parachute had been destroyed.

DLR/MORABA suspects that the thermal shield of the parachute system may have been damaged, and with the structure overheating due to aerodynamic flow, the pyrotechnic initiators of the parachute system opening were triggered. Once initiated, the parachute automatically opened. The aerodynamic flow and heat generated by the air's effect would be responsible for destroying the parachute if opened too prematurely. The recovery system was developed by DLR/MORABA.

Fig. 3. Photo extracted from the front onboard camera during the descent phase at 516.2 seconds of flight. Source: IAE.

5.3. Performing the Joint Analysis

Identification of the Accimap actors involved in the accident/incident for the Joint AcciMap Analysis (Table 2). Due to the missions having common characteristics and being conducted within the same team, the same political and technical conditions and the same organizational environments, the actors are repeated across missions. Six levels will be used to build the AcciMap.

Table 2. Actors of the Joint AcciMap Analysis.

Level	Actors
Government and Budgetary Policy	• PNAE - National Space Activities Program (AEB) • Programme Microgravity (AEB) • European scientific programs for sounding rockets (European Space Agency - ESA - and DLR)
Regulatory Bodies and Associations	• Brazilian Space Agency (AEB)
Government and Local Industry, Company's Management Level	• Brazilian Space Agency (AEB) • Institute of Aeronautics and Space (IAE) • DLR/MORABA (Germany)
Technical and Operational Management	• Institute of Aeronautics and Space (IAE) – Platform / Acceptance tests • DLR/MORABA (Germany) – Platform and Germain Team • Brazilian Space Agency (AEB) - Financing of experiments • Alcântara Launch Center (CLA) - Ground Segment • Barreira do Inferno Launch Center (CLBI) - Ground Segment • Brazilian Air Force (FAB) - Platform recovery operations
Physical processes and actors' activities	• Universities and Scientific Institutions - Experiments
Equipment and Environment	• Sounding Rocket - IAE Responsibility • Microgravity Platform (Recovery system, Control system, Cold Gas System, Yo-Yo System, Telecommunication System) - DLR/MORABA Responsibility • Microgravity Platform (experiment modules) - IAE Responsibility • Scientific experiments - Universities and Scientific Institutions Responsibility • Meteorological Conditions (launch site and splashdown)

Development of AcciMaps for the Cumã (Figure 4) and Cumã II (Figure 5) missions, establishing and linking the elements/factors among themselves within the defined levels in the charts. Due to the similarity between missions, the upper levels contain elements/factors that are repeated.

Based on consultation with an expert in the field, Table 3 emphasizes the identification of common and specific elements/factors for each AcciMap, highlighting the main recurring elements/factors and showing the correspondence of recurring elements/factors between the AcciMaps. It also analyses the criticality of the main recurring elements/factors based on the selected criteria for criticality listed below:

- level of importance in high-level decisions (Governmental);
- level of importance in mid-level decisions (Institutional);
- level of importance in low-level decisions (Operational);

Table 3. Analysis of the AcciMap elements/factors.

	Correspondence of common elements / factors between Cumã/Cumã II	Specific/Not common elements/factors	Critical elements/factors (Cumã/Cumã II)	Observations
Main Recurrent and common elements/factors	01A/01B, 02A/02B, 03A/03B, 04A/04B, 05A/05B, 06A/06B, 07A/07B, 08A/08B, 09A/09B, 10A/10B, 11A/11B	-------	**01A/01B, 02A/02B, 07A/07B, 08A/08B, 10A/10B, 11A/11B**	Numbering of elements/factors guided by AcciMap of the Cumã and Cumã II Missions
Main Specific elements/factors	-------	12A, 12B	-------	
Recurrent and common elements/factors	13A/13B, 14A/14B, 15A/15B, 16A/16B, 17A/17B, 18A/18B, 19A/19B, 20A/20B, 21A/21B, 22A/22B, 23A/23B, 24A/24B, 25A/25B	-------	-------	
Specific elements/factors	29A/26B, 34A/27B, 35A/28B	26A, 27A, 28A, 30A, 31A, 32A, 33A	-------	

As a result, the main critical recurrent elements/factors found are:

a. The Government's lack of interest in elevating the policy of space projects into "state programme";
b. Low launch cadence;
c. Dependence of Brazilian launches on the schedules and interests of the third country;
d. Operational unpreparedness at CLA due to low launch cadence;
e. Delay in technical specifications of the platform;
f. Delay in the development of experiments by universities and research institutions.

Some of the items listed above are classified as risks to be managed, while others are considered issues, the management of which falls under higher-level responsibilities. From this point onward, we will halt our analysis. The remaining tasks include reporting what is relevant to us and recommending the identified issues to higher-level specific forums.

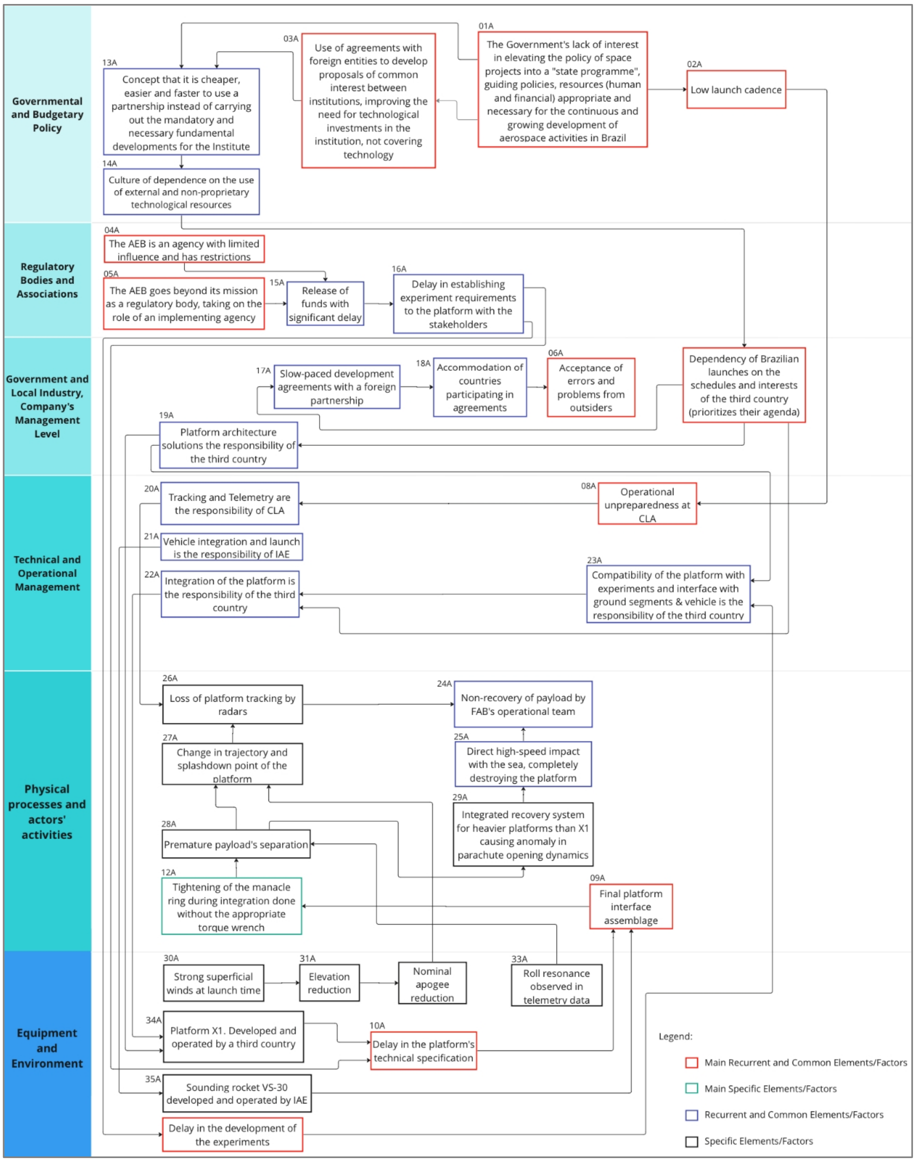


Fig. 4. AcciMap of the Cumã mission.

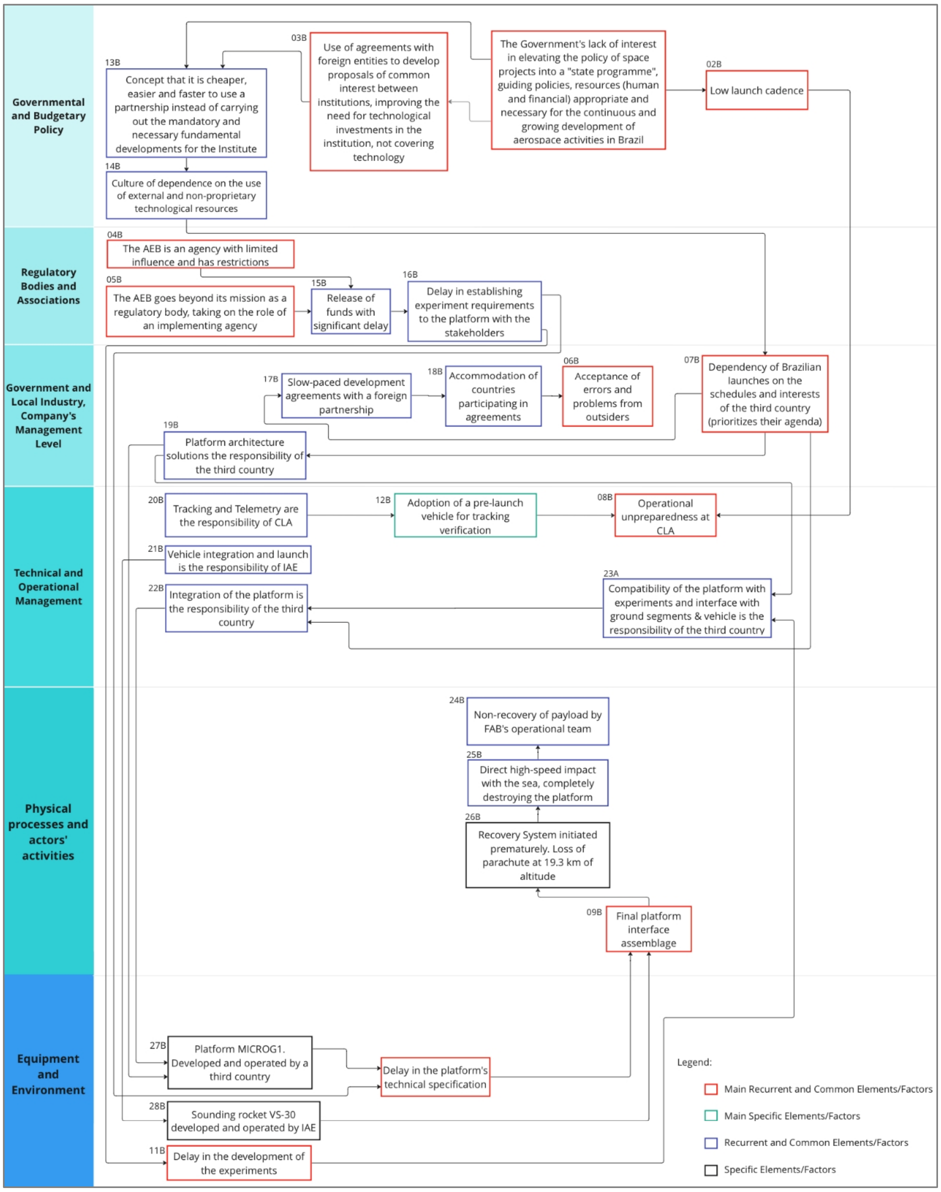


Fig. 5. AcciMap of the Cumã II mission.

5.4. Current limitations of our joint analysis and of our case of study

A significant limitation concerns the origin of the information used in the analyses of our case study. The analysed information is based on secondary sources, i.e., reports issued by AEB contemporaneously with the missions, not directly collected by the authors of this article. However, there was the opportunity to consult an expert who followed the missions to complement the information presented in this article.

Besides, it is important to alert the limitations of a joint analysis. For instance, in this case, although minor, there are differences between the Cumã and Cumã II missions. The first used a VS-30 sounding rocket, while the second used a VSB-30 (different flight regimes). Regarding the platform, both used the same technology, although almost 5 years passed between one mission and another. The main distinction between the platforms relates to the data communication system, where the experiments began to use an auxiliary encoder/decoder system to internally transmit the communication of the greater number of experiments to the platform's data transmitter. The recovery, cold gas, and control systems technologies were retained since they are qualified and are recurrent elements in flights of the German microgravity platforms TEXUS and Mini-TEXUS.

6. Conclusions e recommendations

The completed study introduced the AcciMap method as an indicator of systemic failures among accidents/incidents in scenarios with similar characteristics (e.g.: same organizations, same teams, identical or similar focal objects of accidents/incidents, similar work environments etc.). The use of the original method was expanded to unconventional areas of application, yielding good and interesting results, indicating a significant practical potential for utilization. The proposed analysis would merit a validation process with other case studies for result comparison and strengthen the concept.

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