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The Mapping of Aerospace Meteorology in the Brazilian Space Program: Challenges and Opportunities for Rocket Launch

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ABSTRACT: The meteorological and oceanographic conditions are crucial for the successful launch of aerospace vehicles. However, the decision-making process using environmental information is a complex problem, since it depends on a constant review of current and future weather conditions. To understand this process in the Brazilian Space Program (BSP) context, this paper aims to be the first attempt to map out the systemic view of applied meteorology for the launch missions of aerospace vehicles. Various Brazilian stakeholders were interviewed and their perspectives were analyzed by using a problem structuring method known as Strategic Options Development and Analysis (SODA). With this approach, it was possible to identify different concepts in each group of respondents regarding the current situation of Aerospace Meteorology. One particularly relevant result was identified: weather forecast is not merely a tool to be used to modify the chronology of a mission and to fully provide support in decision-making during the rocket launches in Brazil. Furthermore, the paper shows that the Aerospace Meteorology needs to improve technical processes and to develop a weather decision support system with decision-makers' preferences regarding the uncertainty in weather forecasts. SODA has shown to be a support tool to understand the real situation of meteorology for the launch of aerospace vehicles and appropriate to aid in future planning in the BSP.

KEYWORDS: Spacecraft launching, Decision making, Operational problems, Group behavior, Mapping, Strategy.

INTRODUCTION

The environmental conditions (meteorological and oceanographic) are crucial for the successful launching of aerospace vehicles such as sounding rockets and satellite launch vehicle (Vaughan and Johnson, 2011). Meteorological conditions could also affect other areas of the launch center's infrastructure, therefore it is necessary to take protective action in case of bad weather. However, the decision-making process to protect the facilities of the space center or the exact time of the rocket launch is a complex problem, since it depends on a constant review of current and future weather conditions.

On the other hand, in order to achieve a complete analysis of the decision-making process, it is necessary to evaluate several other factors such as: a) existing operational procedures; b) the limitations of environmental factors; c) current status of the infrastructure of the launching centers, among other factors. In addition to that, the meteorological information should be evaluated by non-expert decision-makers and one should take into consideration all safety requirements during the mission from a systematic approach. That is to say, all weather risks should be evaluated at various stages of the rocket launching procedure, and not just based on the "go" or "no-go" in the launching window.

In the space programs of various countries, many of these procedures have been developed and disseminated in papers and reports (Case *et al.*, 2005; NASA, 2005; Merceret *et al.*, 2006; Kuk *et al.*, 2011; Devyatkin *et al.*, 2012; Dalin *et al.*, 2013). In Brazil, several studies are also being developed in the area of meteorology for rocket launching, for instance, the impact

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of current wind for trajectory (Marciotto and Fisch, 2013), rocket exhaust trails/clouds (Moreira *et al.*, 2011), wind tunnel experiments (Avelar *et al.*, 2012) and also weather numerical modeling (Nascimento *et al.*, 2014). However, decision-making in the aerospace and aeronautical sectors, utilizing weather forecasts, is still a scientific and operational challenge, mainly due to the uncertainty of information (Rabelo *et al.*, 2006; Merceret *et al.*, 2013). Furthermore, weather risk perception and preferences of each decision-maker in relation to the probabilistic weather forecast should also be taken into consideration (Joslyn and LeClerc, 2013).

In order to provide a clear understanding of the process from a systemic point of view, this paper aims to map out the applied meteorology for the launching missions of aerospace vehicles within the Brazilian Space Program (BSP). Various BSP's stakeholders were interviewed, and their perceptions were analyzed utilizing a methodology called Strategic Options Development and Analysis (SODA) (Eden and Ackermann, 2001; Georgiou, 2010). Consequently, it was possible to identify different concepts in each group of respondents regarding the current situation of Aerospace Meteorology in Brazil and its relation to the use of weather forecasts on mission launching.

BACKGROUND

BRAZILIAN SPACE PROGRAM

Brazil has been developing its space program since 1965, which begun with the launching of a sounding rocket within Brazilian territory (Brasil, 2008; AEB, 2012). In the late 1970s, the Brazilian government established the "Brazilian Complete Space Mission", which defined the long-term goals of the BSP: that is to say the launching of a Brazilian satellite, with a rocket manufactured and from a launching center in Brazil (Ceballos, 1995).

BSP is currently going through a restructuring process organized by the Brazilian Space Agency, the Ministry of Defense and the Ministry of Science, Technology and Innovation (Brasil, 2012). Furthermore, the BSP has found itself aligned with a new international aerospace industry trend; in other words, it is relying on a greater participation of the private sector (Devezas *et al.*, 2012). In order to make this feasible and to bring a spirit of dynamism to this sector in Brazil, the BSP has created two companies. The first one is the Alcântara Cyclone Space (ACS), a bi-national company (Brazil and Ukraine) to operate the satellite launch vehicle Cyclone-4. The second company is Visiona Corp, a joint venture created from the association between EMBRAER and TELEBRAS, in order to develop the Geostationary Defense and Strategic Communications Satellite (AEB, 2012; Brasil, 2012).

Through the ACS Company, Brazil currently has the possibility of performing satellite operations with liquid propulsion launch vehicles from a Brazilian space center. The Cyclone-4 rocket has the capacity to put into geostationary orbit satellites of up to 1.600 kg (Brasil, 2012; Devezas *et al.*, 2012) and can place Brazil in the private satellite launch market. This context motivated to analyzes the meteorological applications within the BSP.

AEROSPACE METEOROLOGY AND ROCKET LAUNCHING

Weather and climate conditions strongly influence all phases of an aerospace launching mission, to which we highlight:

- Planning: climatological conditions.
- Pre-launching (installation and integration of aerospace vehicle): forecasting and monitoring of weather conditions that can damage the infrastructure of the rocket and the facilities of the launch center.
- Launch (liftoff and tracing the trajectory of the rocket in the atmosphere): observations in real-time and short-term forecasting (nowcasting) of environmental variables (meteorological and oceanographic).
- Post-launch: monitoring and evaluating the impact of weather conditions on the dispersion of the rockets' exhaust gases, payload recovery (for sounding rockets) and the stages of vehicle (for space vehicles), among other activities.

Events in other space programs show that the impact of weather conditions during a mission rocket launch can be critical. For example, during the launch of Apollo XII, in November 1969 (the second manned mission to the moon), the Saturn-V rocket was struck by lightning, which resulted in a computer crash aboard the aerospace vehicle (Uman and Krider, 1989). Despite the fact that the on-board instruments were restored moments later, this event caused significant changes in the operational procedures in the future launches of the United States' space program.

On the other hand, some of the consequences of inclement weather conditions in launch missions may have indirect effects. According to Vaughan (1996), in January 1986, a weather event caused low temperatures at the Kennedy Space Center

(NASA's launching center) — the same week of the Mission of Space Shuttle Challenger. The freezing temperatures, and other factors, caused the O-rings of the rocket fuel tanks to be damaged, originating leaks and, later, the Challenger explosion during launch.

Using probabilistic weather information in decision making process is difficult and requires an analysis of the environmental conditions in an integrated, rational and objective manner. It is remarkable to mention that, for complete success in launching a rocket, various activities are important at different stages of the launch mission. Moreover, the atmospheric conditions are relevant in defining the exact time of the launch window. Thus, all activities related to environmental and atmospheric science that can have an impact on rocket launching missions are classified as Aerospace Meteorology (AM) (Vaughan and Johnson, 2011).

METHODOLOGY

PROBLEM STRUCTURING

One purpose of problem structuring methods is to understand the objectives and perceptions for each of the stakeholders involved in the decision-making situation. For this, several approaches have been intensively used since 1970, when consultants, decision-makers and analysts realized that, by using this method, they would be able to explore, understand and thus make better decisions in order to improve the organizational context under their responsibility (Rosenhead and Mingers, 2001; Georgiou, 2010).

However, there were still some gaps. At the end of the 1980's, a group of researchers devised a new method designated Strategic Options Development and Analysis (SODA), which took place as a primary tool for cognitive mapping, combined with George Kelly's psychological construct theory (Ackermann and Eden, 2001; Georgiou, 2009). SODA is intended to be a method of structuring and problem identification (Eden, 2004; Manso *et al.*, 2015). Through cognitive mapping, and consequently through a hierarchical structure of concepts, individual perceptions of problematic situations are recorded and elicited (Ackermann and Eden, 2001). Individual mappings can be merged, providing a synthesis of the group's perception (Eden, 2004). The final result is a map that provides the analyst with an overview of the investigated context (Rosenhead and Mingers, 2001).

It is necessary to emphasize, however, that the main differences between classical cognitive maps and SODA maps are the theoretical foundations of the SODA, which appropriates part of Kelly's theory of psychological constructs (Georgiou, 2010). Briefly, it can be said that what is called "concept" in cognitive maps is called "construct" in the SODA map. These constructs represent the informal knowledge of the decision-maker and are designed to eliminate ambiguity and subjectivity that may be present in the statements of each client (Ackermann and Eden, 2001; Georgiou, 2009).

In order to make this feasible, we use the so-called "opposite poles" (bipolar design). These are statements about certain actions, situations, or observations separated by three dots and followed by another contrasting statement, able to sufficiently eliminate ambiguity, subjectivity, or even able to clarify the context of what was analyzed (Georgiou, 2010). An example of this approach is shown in Table 1.

Table 1. Example concepts of respondents.

Interviewee	Concepts	Opposite pole
Decision-maker A	Weather forecast is not useful...	Information is accurate
Decision-maker B	Weather forecast is not useful...	Format is suitable

For both decision-makers (A and B), the weather forecast does not appear to be useful. However, by applying the contrast to both of the statements, it is possible to identify the individual (and different) points of view. Therefore, one realizes that the weather forecast may be useful for decision-maker A, if the information presented is accurate. On the other hand, in order to make the weather forecast useful for decision-maker B, the format must be suitable for the intended application.

Henceforth, one may note that the main focus of SODA is to eliminate inherent ambiguities and to provide a clear view of the context under analysis, thus enabling the identification of potential solutions or courses of action emerging from the different perceptions (Georgiou, 2009; Manso *et al.*, 2015). The SODA map is usually employed in the primary stages of approach, when one does not have a clear idea of the context under investigation. However, in some cases, one has verified that the method used to screen more advanced stages serves as decision support, or as a starting point for methods such as system dynamics.

MAPPING OUT AEROSPACE METEOROLOGY

In rocket launch missions, meteorological conditions and weather forecasts are provided, passed on and used by different actors. So, for the systemic mapping of AM in the Brazilian Space Program, several stakeholders, divided into three groups, were interviewed:

- Technical staff (seven interviews): professionals directly related to the provision of weather forecasting and meteorological observation, as meteorologists, engineers and support staff.
- Direct users (ten interviews): actors who use the meteorological information and weather forecasts, directly in their activities during launch missions, and are responsible for the payload, flight safety, team assembly and integration etc.
- Top decision-makers (six interviews): considered to be senior managers in the launch missions and/or the BSP, such as chief operating officer, coordinators and/or directors of the institutions involved.

Thus, a total of 23 professionals in the BSP, spread over 5 different organizations, were interviewed. Through interviews with different stakeholders, it was possible to identify the perceptions of each group in relation to AM and weather forecasts. Surely, these perceptions are related to their various activities in the rocket launch missions, such as infrastructure, personnel etc. According to the SODA method, individual maps of each stakeholder were made. Subsequently, the individual maps were gathered in each group and validated by the highest ranking member (senior) of each respondent group. As a final step, a map aggregate was made of the three group's stakeholders, whom we called the "merged map".

RESULTS AND DISCUSSION

MAPS AND CLUSTER CLASSIFICATION

When all the interviews were finished, the constructs were also classified according to the focus pointed out by the interviewees. In other words, the concepts were grouped into thematic clusters, divided into six different sets:

- Management: constructs related to aspects of legislation, regulation, budget, political support and institutional support for the space program.
- Infrastructure: related to the infrastructure of the launch centers and meteorological activities such as equipment and instrumentation.
- Operational: constructs directly related to the operational activities of the space center, mission launches or decision-makers/managers.
- Staff: related technical staff and other space program professionals.
- Processes: constructs related to the systems and procedures of launch missions.
- Future vision: related to aspects of long-term vision for the future of the BSP.

Table 2 shows the amount of each set of constructs indicated by the stakeholders added and the merged map, separated by clusters.

So, the stakeholders mentioned a total of 118 constructs, which were then merged together and validated by the interviewees, reaching a final total of 74 constructs. The reduction of constructs between the gathered maps from each group and the merged maps is because, quite often, the concepts of each group are similar and can be grouped together in the final version of the SODA map. A complete list of the 74 constructs separated by clusters appears in the Appendix of this paper.

HEAD AND TAILS

Given the properties of the SODA map, it is possible perform a number of detailed analysis of a problematic situation. In the supporting merged map (final version), the "head" may be considered the goal (or goals). That is, through the respondents' perceptions of meteorology, it was possible to define a single objective, which, in this case, is the use of weather as an effective

Table 2. List of constructs by cluster and stakeholder group.

Issue (clusters)	Technical staff	Users	Top decision-maker	Total	Total merged map
Management	4	3	4	11	**9**
Infrastructure	6	5	3	14	**8**
Operational	2	7	9	18	**15**
Staff	5	2	4	11	**7**
Processes	11	13	17	41	**28**
Future vision	4	7	12	23	**7**
Total	**32**	**37**	**49**	**118**	**74**

tool for decision support during rocket launch mission (construct 71, Fig. 1). In other words, the weather forecast (WF) does not modify the activities stipulated in the launch chronology.

As mentioned in the methodology section, through the bipolar design of the SODA map, it is possible to diagnose, to "identify weather risk" and to "establish which procedures in the launch mission" should be followed through, so that the objectives are achieved (construct 71). Another important feature of Fig. 1 is that the constructs with immediate links to a "head" are called "strategic options". That is, these constructs (26, 54, 60, 64 and 70) are possible strategic options available for achieving the objective.

Therefore, in view of the interviewed group, the "strategic options" for the use of weather as a tool for decision support in rocket launch missions in Brazil are presented in Table 3 (in bold).

Grouping by clusters of strategic options, one is in "future vision" (construct 70), three are in "processes" (54, 60 and 64) and one is related to "operational" (26), as demonstrated in the Table 4.

The tails are considered to be the primary cause of the problematic situation. That is to say, for this study, they are the initial concepts that lead to the inappropriate use of weather forecasts in launch missions. In the SODA map, the tails provide a trace of the origin whose state will influence the effectiveness of the goal and its strategic options. In Table 5, the list of 10 identified tails is presented.

It is possible to identify as origin that some concepts are not directly related to AM, for example, the lack of financial resources (construct 8). This can also be seen in the division of concepts into clusters (Table 4): 1 construct in "management" (8), 5 in "infrastructure" (12, 14, 15, 16 and 17), 3 in "operational" (20, 21 and 22) and one related to "future vision" (72). Interviewees perceived the problems of infrastructure and operations as being the initial causes for not using the weather forecast as an integral tool in launch missions. An example of infrastructure highlighted by one interviewee is: "the absence of a comprehensive system of lightning detection at the launch center increases the weather risk" (construct 16, Table 5). Another example is that there are few launch missions in Brazil per year and consequently this also causes a lack of qualified technical personnel (construct 22, Table 5).

IMPLOSIONS, EXPLOSIONS, AND DOMINATING CONSTRUCTS

The relationship between the constructs of the SODA map also allows some other interpretations. In the construct with the largest implosion map (construct 60), *i.e.* the construct that has various constructs leading into it (indegree = 8), it is possible to identify the multiple aspects of the existence of "high risk in decision-making using weather forecasting" (Fig. 2).

In the respondents' point of view, the eight constructs (connected to dominant) are directly related to the risk of making decisions

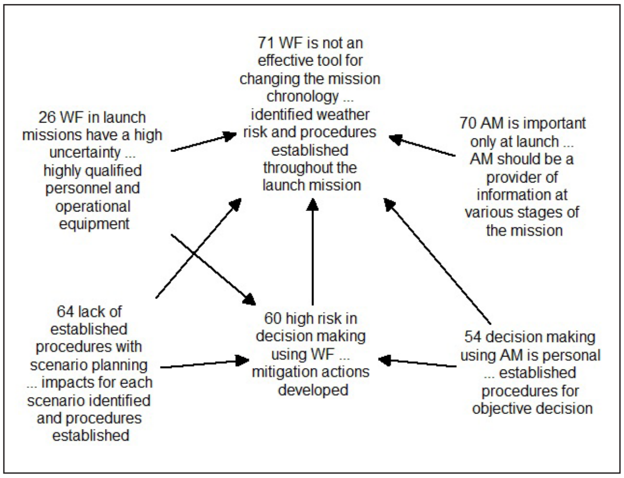

Figure 1. Strategic goal (71) and identified strategic options of the final SODA map.

Table 3. Strategic options and their bipolar design of the construct.

Strategic options
26 WF in launch missions have a high uncertainty... **highly qualified personnel and operational equipment**
54 decision making using AM is personal... **established procedures for objective decision**
60 high risk in decision making using WF... **mitigation actions developed**
64 lack of established procedures with scenario planning... **impacts for each scenario identified and procedures established**
70 AM is important only at launch... **AM should be a provider of information at various stages of the mission**

Table 4. Construct number of tails, heads, strategic options and dominants in the merged map.

Issue (cluster)	Tails	Heads	Strategic options	Dominants (> 4)
Management	1	0	0	4
Infrastructure	5	0	0	1
Operational	3	0	1	3
Staff	0	0	0	1
Processes	0	0	3	15
Future vision	1	1	1	1
Total	**10**	**1**	**5**	**25**

planning utilizing meteorological scenarios (64). The planning scenario related to potential weather events that could negatively impact the launch mission is of great importance for this group of stakeholders.

On the SODA map, the explosion indicates that the construct has a strong influence on the merged map and therefore on the objectives of the problematic situation. There was also a consensus among the three groups of respondents that the lack of operational procedures and the need to identify all the weather-related information demands during the launch mission chronology are an extremely important issue. This feature can using weather forecasts. These constructs indicate the need for improvements in the identification of meteorological impacts (construct 46), the observation of environmental conditions in real time (44), the definition of the risks and establishment of procedures (40, 54, 55, 64 and 67), as well as keeping qualified technical staff and equipment operating/ready for use (26).

Similarly, the SODA map makes also possible to identify those constructs in which "explosion" occurs, that is, when ideas influence various constructs. In Fig. 3, it is shown that, in construct 56, "few operating procedures are related to AM" and that number has increased connections (total of 8) in the entire model. In other words, there are few sets of procedures that have a direct bearing on the quality and format of weather information (constructs 49, 50, 53, 61, 63 and 66), on the lack of an integrated decision support system (47) and on the lack of

Table 5. Tails in the merged map.

Identified tails
8 low valuation of the space program... sufficient financial resources
12 deficient software of AM (weather systems integration)... software available and operational
14 poor communication data... dedicated link to weather data
15 deficient reception of satellite image... own system available
16 poor lightning and electrical field detection system... financial resources available
17 lack of an observation backup system... multiple observation systems
20 poor training of new staff... replacement staff and continuous training
21 Brazilian rockets are susceptible to weather conditions... rockets with a high protection
22 poor operational team in launching centers... periodic and continuous launch
72 maturation of the importance of "customer"... lack of experience with external payload organizations BSP

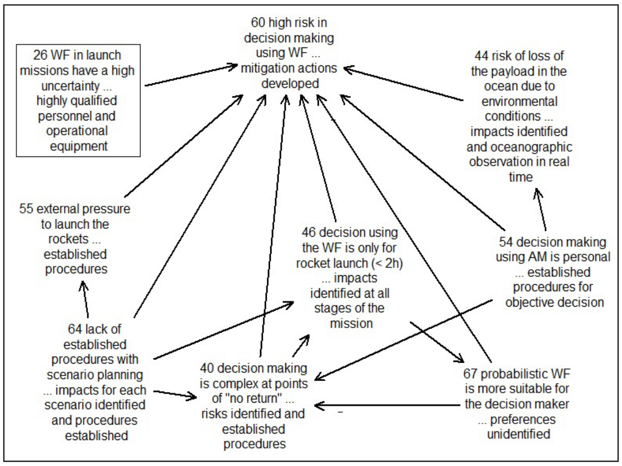

Figure 2. Construct (60) with more implosion on the merged map.

Table 6. Dominant constructs (degree > 7) in the merged map.

Dominant constructs
40 decision making is complex at points of "no return"... **risks identified and established procedures**
46 decision using the WF is only for rocket launch (< 2h)... **impacts identified at all stages of the mission**
47 lack of a weather decision support system... **system designed in accordance with Brazilian demands**
53 WF format is not suitable... **procedures established for each type of mission/rocket**
56 few operating procedures related to AM... **identified demands**
60 high risk in decision making using WF... **mitigation actions developed**
64 lack of established procedures with scenario planning... **impacts for each scenario identified and procedures established**

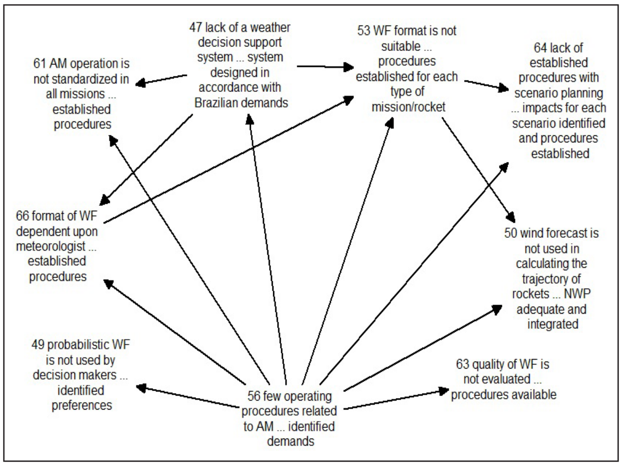

Figure 3. Construct (56) merged with larger explosion in the map (NWP = numerical weather prediction).

also be observed in Fig. 4, which shows the construct 56, that is also the dominant construct in the merged map. In this case, concept 56 has a total of 12 (high total) numbers of constructs connected to it. According to Georgiou (2009), dominants can be interpreted as constructs in a map and indicate focal points in the model where issues or decisions converge to (diverge from) the map.

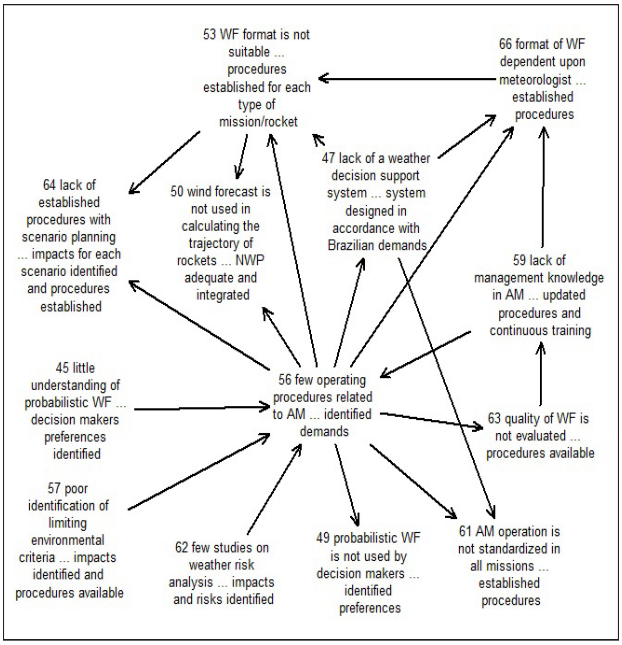

Figure 4. Dominant construct (56) in the merged map.

Naturally, these constructs should be analyzed carefully, as decisions related to the dominant constructs are connected to many other concepts and have a high impact on the model. In Table 6, some dominant constructs (> 7, sum of indegrees and outdegrees) are presented. The actions that should be taken to promote the strategic options are highlighted (in bold).

So, for the most relevant dominant constructs (Table 6), there are three sets of actions that should be taken:

- Identify all demands (construct 56), risks and impacts (40, 46 and 64), as well as mitigation actions related to AM (60).
- Establish operational procedures at various stages of each type of mission and rocket (46 and 53).
- Develop the weather decision support system in accordance with Brazilian demands (47).

FEEDBACK LOOPS

In the SODA map, it is also possible to identify improvement opportunities in a problematic situation (Ackermann and Eden, 2001). This feature is evaluated by feedback loops between the constructs, and can be useful for identifying areas of degenerative or regenerative dynamics. The loops may represent situations of the collapse of a particular decision-makers' concept. In Fig. 5, we have the main feedback loops of the merged map.

The loop constructs 32, 18 and 28 show a degenerative cycle due to the lack of confidence in the weather forecast

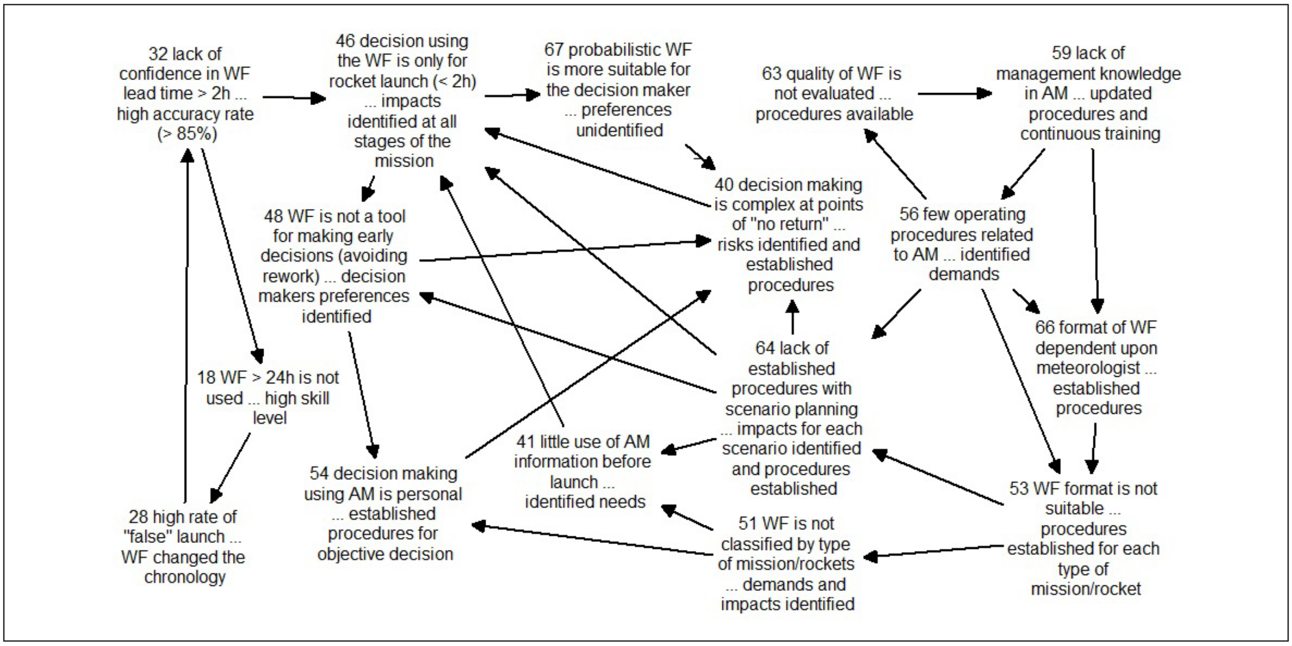

Figure 5. Main feedback loops of the merged map.

because it is not used for periods > 24h, which causes a high rate of false launches. Note that the false entries occur when the countdown is not halted, even with the bad weather forecast. However, when the launch is canceled or postponed around the liftoff window, it causes delays in the space mission and technical staff discontent.

According to some interviewed actors, the false launch can be a big issue, since many sounding rockets need to be integrated several hours before liftoff, and, after numerous false launches, this unnecessary repetition can impair the safety of the mission.

In another loop, constructs 46, 67 and 40 indicate that decision-making using meteorological information only occurs for weather forecasts of up to 2h before the rocket launch. According to respondents, this happens because the impacts, probabilities of accuracy and weather risks were not previously defined. In other words, if the forecast is for bad weather, the decision to cancel the launch is delayed up to a maximum of 2h before the original schedule. This situation is directly related to the false launch, as shown in the previous loop.

For this group of stakeholders, the probabilistic weather forecast (and not deterministic, as it is currently used) would be more appropriate (construct 67). Another negative effect highlighted by respondents of the current model is that decision-making at the point of no return in the launch chronology. This is an extremely complex and challenging moment of the operation because it depends on an individual subjective decision (construct 40) from the Chief Operating Officer responsible for the mission. The point of no return is considered when some rocket system is activated in advance (*e.g.* fuel) and cannot be turned off. That is, even though at the exact time of liftoff there is weather with values above the operating limits, the rocket has to be launched and/or destroyed via remote command.

The loop constructs 40, 46, 48 and 54 show that the preferences and values of decision-makers regarding weather forecasts have not been identified yet, so the decision to use Meteorology information is personal. That is, even if the launches are similar, the decisions could be distinct because they depend on the profile and experience of the Chief Operating Officer.

In Fig. 5, it is also possible to observe the looping of the constructs 56, 63 and 59. This loop indicates that the lack of AM-related procedures negatively impacts the quality of the weather forecast, *i.e.* the hit rate of the forecast is not evaluated. Interviewees perceived this situation as a lack of knowledge between the management and the technical team and also an proper training of new meteorologists.

IMPACTS OF WEATHER INFORMATION FOR ROCKET LAUNCHES

Regarding the constructs identified by stakeholders, some are directly related to the development of weather forecasting and how it is used in the launch mission. Table 7 presents the features of 5 constructs that define technical parameters related to weather forecasting and that can be applied in the parametrization of new decision support systems.

So, in the view of respondents, a weather forecast beyond 24h is not used in decision-making (constructs 18 and 32), due to the low rate of success (< 85%). That is, even if the weather conditions are unfavorable, the decision-makers choose to wait for an updated weather forecast closer to the event, up to 2h before (constructs 32 and 46). In this case, the event can be any chronology activity, where any weather conditions could be a limiting condition (*e.g.* integration rocket on the launch pad).

However, the most important concept regarding weather forecasts is that the values and profiles of decision-makers are not fully identified yet. That is, the interaction with decision-makers showed that it is important to incorporate context in this problem along with the uncertainty of the weather prediction. Therefore, it is mentioned (constructs 47 and 48) that the challenge is to develop a new weather decision support system, as well as to identify and quantify the preferences of the decision-makers, concerning the inherent risk in forecast uncertainty. Nevertheless, in order to incorporate the decision-maker's preferences regarding weather prediction, it would be necessary to develop a new decision support system with a systemic view:

- Identify the demands for weather information throughout the launch mission (construct 46).
- Quantify weather risk to the rocket and the launch center facilities (40).
- Develop a scenario plan (64) for associated weather conditions.
- Develop mitigation actions for each type of scenario, mission and rocket (53 and 60).

CHALLENGES AND OPPORTUNITIES

As a final set of challenges and opportunities for AM in Brazil, we elaborate Tables 8 and 9 based on the concepts of the respondents and our experience in the BSP. Note that these lists are directly related to meteorology. As discussed previously, the improvement opportunities for the problematic situation can be identified by the feedback loop of the SODA map (Fig. 5). In Table 9, the opportunities listed also meet the

Table 7. Constructs directly related to the operation of the weather forecast.

Features of constructs
18 WF > 24h is not used… high skill level
32 lack of confidence in WF lead time > 2h… high accuracy rate (> 85%)
46 decision using the WF is only launch (< 2h)… impacts identified at all stages of the mission
47 lack of a weather decision support system… system designed in accordance with the Brazilian demands
48 WF is not a tool for making early decision (avoid rework)… decision-makers' preferences identified

Table 8. List of key challenges identified.

Challenges	Constructs related
Expand technical staff of Meteorology, maintain qualification and continuous training	4, 19, 20, 33, 34, 35, 36, 38, 39 and 59
Expand and maintain instruments for meteorological and oceanographic observation in full operation	2, 9, 26 and 44
Establish all operational procedures related to AM at the different stages of the chronology of release and classified by type of mission and rocket	25, 40, 52, 53, 54, 55, 56, 57, 58, 59, 61, 63, 66, 70 and 71
Identify and quantify weather risk and mitigation actions in different meteorological scenarios during missions launch	6, 7, 30, 40, 43, 60, 62, 64 and 71
Expand research and development projects related to AM in the Brazilian launch centers, particularly in regional numerical modeling, gas dispersion launches (rocket exhaust clouds) and meteorological hazards	6, 39, 42, 43, 58, 62 and 71

Table 9. List of identified opportunities.

Opportunities	Constructs related
Identify needs for weather information at all stages of the rocket launch mission (not only the liftoff)	43, 46, 47, 48, 51, 54 and 56
Increase interaction between teams of Meteorology, users and decision-makers to develop appropriate procedures in AM demands by type of mission and rocket	28, 40, 52, 53, 54, 55, 56, 59, 61, 63, 64, 66 and 71
Develop products with probabilistic weather forecast (e.g. ensemble)	32, 45, 49 and 67
Develop new projects of research and development in areas related to atmospheric science such as space weather, oceanographic and meteorological instrumentation applied to aerospace	1, 10, 40, 43 and 44
Develop a new weather decision support system, according to the preferences of users and decision-makers from Brazilian Space Program	18, 45, 48, 49, 54 and 67

concepts of the loops of the constructs 18, 32 and 28 (left side of Fig. 5) and the loop 46, 67 and 40 (on the top of Fig. 5). That is, the increasing confidence of users and decision-makers in weather forecasting enables early decision-making (before 24 h) thus avoiding false launches.

CONCLUSIONS

This paper aimed to be the first attempt to map out the systemic view of Aerospace Meteorology at the Brazilian Space Program. The problem structuring methods applied in this study, through interviews with stakeholders, stimulated an overview about the identification and evaluation of weather information for the launch of aerospace vehicles. The SODA map approach increases the decision-maker's knowledge to analyze the problem, since it helps clarify the alternatives and facilitates the understanding of the preferable options needed to apply weather forecasts for the launch mission.

According to the group of Brazilian stakeholders, the constructs related to this problematic situation are divided into 6 clusters (Table 2). By utilizing the SODA method, it was possible to make a set of assessments of decision-makers' values and perceptions by using the constructs of the merged map. As a highlight, we found that the lack of procedures in Aerospace Meteorology (total of 28 constructs) and operational problems at launch mission (total of 15 constructs) constructs were most often remembered by respondents (Table 2). In this context, it has been determined that a weather forecast is not merely a tool to be used to modify the chronology of a mission and to fully provide support in decision-making during the rocket launches in Brazil.

As the strategic objectives for AM in Brazil have been defined by this mapping, weather forecasts should become an effective tool for decision support in launch missions. The initial reasons given by respondents for this strategic objective have not been achieved; the problems are concentrated in infrastructure (constructs 12, 14, 15, 16 and 17 of Table 5) and operational problems during launches missions (20, 21 and 22 of Table 5). On the other hand, there are also some reasons indicated by respondents, which had no direct relationship to AM, for example, the lack of resources for the space program (8) or even changes in the customers' perception of the importance of microgravity research or other payload experiments (72). This also shows that improving Aerospace Meteorology during the launch missions is beyond the activities of the weather forecast.

The strategic options identified by the SODA map (constructs connected to the objective) are clearly concentrated in the absence of processes (constructs 54, 60 and 64 of Fig. 1) during launch mission. As a direct effect, decision-making is personalist (54) and the decision to use the weather forecast is considered highly risky by the decision-maker (60). Furthermore, through the implosions, explosions, dominants and feedback loops, it was possible to identify other highly relevant concepts for the operation of the weather forecast.

We must emphasize this need to develop a weather decision support system, in accordance with the decision-maker's preferences (47 and 56), classified by type of mission and weather scenario planning in rocket launching operations (53 and 64). In other words, forecasts are uncertain, and the resulting risk may be interpreted differently by different decision-makers, depending, in part, on their personal experience and risk perception. In this case, to apply a weather forecast as a reliable tool for decision-making, one needs to incorporate three specific preferences on the demands, procedures, and impacts, which are listed below:

- Value of meteorological variables (wind, rain), according to the boundary conditions of the aerospace vehicle and the launch center facilities (constructs 21, 29 and 53).
- Lead time of the weather forecast (hours, days), *i.e.* the expiration date of the weather prediction presented to the decision-maker (constructs 18, 32 and 46).
- Probability of the weather forecast (%), associated with each variable and lead time (constructs 32, 45, 49 and 67).

Certainly, the challenges related to Aerospace Meteorology have a strong relationship with the challenges of the BSP. For example, to extend the network of meteorological and oceanographic instruments, it is necessary to have consistent funding for the acquisition and maintenance of equipment. In opposition, identifying weather risks and developing mitigation actions throughout the launch mission require greater interaction between the various BSP's organizations and the different technical teams.

Through this mapping, it was possible to identify the main challenges and opportunities (Tables 8 and 9) for improvement within the AM in the BSP. Surely, this is not an exhausted process and requires constant assessment over the years. We must be constantly developing appropriate meteorological products in accordance with the preferences of users and customers. This is a permanent challenge for the meteorologist and technical team. However, in a space program, where risks and costs are much higher, this approach is crucial to the safety of staff and infrastructure.

As a final remark, the SODA map has shown itself to be quite useful for this case, facilitating the understanding of the AM's real situation in the BSP. Furthermore, applying this method in a real case has shown to be a completely appropriate and a reasonable choice for aerospace decision-making problems. In this sense, we can say that the use of problem structuring methods as a first step for decision-making situations is definitely the best option for complex decisions to be made in some topics such as space program planning and/or defense sector.

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Appendix 1. List of 74 constructs in Merged Map.

Constructs	Cluster	Connection
1 delay in deployment of meteorological instruments... awareness of the importance	Management	+13 +53 +40
2 limited financial resources for equipment and infrastructure for AM... available resources		+1
3 low priority by senior management in the AM activities... awareness of the importance		+37 +2 +4 -7
4 specific and ongoing training deficient in AM... awareness of the importance		+52 -7
5 deficient development of long-term infrastructure plan... awareness by senior management		+13 +1 +2
6 maturation of the importance of AM... low weather risk perception		-63 -59
7 risk perception increased after the VLS accident... low perception of Brazilian decision-makers		+9 +6 -1
8 low valuation of the space program... sufficient financial resources		+35 +27 +2 +3 +5
9 reliability of equipment/data of AM are important... low weather risk perception		-1
10 deficient observation instruments for AM... instruments installed and fully operational	Infrastructure	+13
11 NWP inadequate for the mission launch... regional models and short-term WF		+13
12 deficient software of AM (Weather Systems Integration)... software available and operational		+47 +13
13 insufficient general infrastructure for AM... center suitable for all launching operations		+44
14 poor communication data... dedicated link to weather data		+13 +11
15 deficient reception of satellite image... own system available		+10
16 poor lightning and electrical field detection system... financial resources available		+10
17 lack of an observation backup system... multiple observation systems		+10
18 WF >24h is not used... high skill level	Operational	+28 +26
19 limited staff with experience in AM... periodic and continuous launch		+26
20 poor training of new staff... replacement staff and continuous training		+24
21 Brazilian rockets are susceptible to weather conditions... rockets with a high protection		+30 +31 +23 +29
22 poor operational team in launching centers... periodic and continuous launch		+24 +25 +19
23 AM is subject to flight safety team... implementation of WF at different stages of the mission		-31
24 lack of a systemic view of the launch missions... interactions identified and teams prepared		+28 +23
25 low weather risk perception... continuous launches and developed operational culture		+24 +18 +28
26 WF in launch missions have a high uncertainty... highly qualified personnel and operational equipment		+71 +60
27 lack of interaction between BSP organizations... periodical and continuous launches		+24
28 high rate of "false" launch... WF changed the chronology		+32 +26
29 AM information is relevant at different stages of the mission... low interaction with other sectors		-41 +31
30 accuracy of AM is an important safety factor... activities with low weather risk		+67 -26
31 WF is important throughout the mission chronology... rocket more resistant to environmental conditions		+30
32 lack of confidence in WF lead time > 2h... high accuracy rate (> 85%)		+18 +46 +26
33 hard work during mission launch... no need to move outside staff	Staff	+39
34 few forecasters with experience in AM... ongoing training and interaction with more experienced staff		+36
35 high staff turnover in the BSP organizations... adequate career progression and challenging conditions		+27 +37
36 few forecasters and technical teams... adequate operating staff		+38 +39 +33
37 difficulty in keeping meteorologists and technical staff in the launch center... good infrastructure for housing		+34 +36
38 need to move technical staff for missions launch... local staff available		+39
39 difficulty in conducting research in AM... local and permanent staff available		+42
40 decision making is complex at points of "no return"... risks identified and established procedures	Process	+46 +60
41 little use of AM information before launch... identified needs		+46
42 low interactions between R&D and operation... identified needs		+57 +58 +43 +62
43 nonexistent research in space weather and launching rockets... demands and risks identified		+62
44 risk of loss of the payload in the ocean due to environmental conditions... impacts identified and oceanographic observation in real time		+60
45 little understanding of probabilistic WF... decision-makers' preferences identified		+56
46 decision using the WF is only for rocket launch (< 2h)... impacts identified at all stages of the mission		+67 +48 +60
47 lack of a weather decision support system... system designed in accordance with Brazilian demands		+61 +53 +66 +55 +48
48 WF is not a tool for making early decisions (avoiding rework)... decision-makers' preferences identified		+40 +54
49 probabilistic WF is not used by decision-makers... identified preferences		+48 +40 +54 +46
50 wind forecast is not used in calculating the trajectory of rockets... NWP adequate and integrated		+44 +51
51 WF is not classified by type of mission/rockets... demands and impacts identified		+41 +54 +61
52 poor interaction between AM and other sectors... well-established procedures and hierarchy		+45 +57 +42
53 WF format is not suitable... procedures established for each type of mission/rocket		+44 +64 +50 +51
54 decision making using AM is personal... established procedures for objective decision		+71 +44 +40 +60
55 external pressure to launch the rockets... established procedures		+60
56 few operating procedures related to AM... identified demands		+49 +64 +53 +66 +47 +50 +63 +61
57 poor identification of limiting environmental criteria... impacts identified and procedures available		+56
58 little research on the gas dispersion launches (rocket exhaust clouds)... high interaction between R&D and operation		+62
59 lack of management knowledge in AM... updated procedures and continuous training		+66 +65 +56
60 high risk in decision making using WF... mitigation actions developed		+71
61 AM operation is not standardized in all missions... established procedures		+55
62 few studies on weather risk analysis... impacts and risks identified		+56 +44
63 quality of WF is not evaluated... procedures available		+59
64 lack of established procedures with scenario planning... impacts for each scenario identified and procedures established		+71 +48 +60 +41 +55 +40 +46
65 Brazilian standards based on international standards... appropriate standards for Brazilian characteristics		+47
66 format of WF dependent upon meteorologist... established procedures		+53
67 probabilistic WF is more suitable for the decision-maker... preferences unidentified		-60 -40
68 environmental impact is a concern in commercial launch missions... disinterest in the international market	Strategic	+69
69 rocket and launch center cannot present problems/delays for commercial missions... interest only in R&D missions		+73 -70
70 AM is important only at launch... AM should be a provider of information at various stages of the mission		+71
71 WF is not an effective tool for changing the mission chronology ... identified weather risk and procedures established throughout the launch mission		Head (strategic objective)
72 maturation of the importance of 'customer'... lack of experience with external payload organizations BSP		+74 +69 +68
73 international experience valued AM... low weather risks perception from Brazilian decision-makers		+70
74 quality certification is important for commercial missions... disinterest in the international market		+73