The Joint Application of Functional Resonance Analysis Method (FRAM) with the Perceptual Cycle Model (PCM) Supporting the Safety Analysis of an Accident.

Igor Neves Marques da Silva, Guilherme Manfrim Siviero,
Fernando Antônio Pereira and Moacyr Machado Cardoso Junior

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Igor Neves Marques da Silva

Aeronautics Institute of Technology (ITA), Brazil. E-mail: gorneves@gmail.com

Guilherme Manfrim Siviero

Aeronautics Institute of Technology (ITA), Brazil. E-mail: guilherme_manfrim@outlook.com

Fernando Antonio Pereira

Aeronautics Institute of Technology (ITA), Brazil. E-mail: fernando.a.pereira.54@gmail.com

Moacyr Machado Cardoso Junior

Aeronautics Institute of Technology (ITA), Brazil. E-mail: moacyr@ita.br

The increasing automation and complexity in aircraft systems may present considerable challenge to flight crews all over the world and concerns related to human machine interface appears, mainly in a stressful situation and potentially lead to an accident. This study proposes use the FRAM tool to reconstruct an event scenario to bring clear comprehension in the everyday performance adjustments and to allow characterize the main points where the variability of human performance, in a given specific situation, could lead to an observed negative result. In addition, this paper also proposes the application of the Perceptual Cycle Model (PCM) in the analysis of naturalistic decision-making coupled to the FRAM model. In July 2007, the Airbus 320 of TAM Airlines flight JJ3054 destined to São Paulo lost control on the ground and overran the runway. The PCM usage highlighted the flight crew behaviour and course of actions operating the thrust levers given the information received and the pilots schema at that moment. With the understanding obtained from the PCM application, it is possible to feed back the FRAM model improving the comprehension of the accident scenario and key points affecting the human performance variability, enabling manage it. The joint application of FRAM and PCM proved to be a great contribution to accident prevention and the engineering of more resilient complex dynamic sociotechnical systems.

Keywords: Accident Investigation, Safety Analysis, Functional Resonance Analysis Method, Perceptual Cycle Model, Naturalistic Decision Making, Human Performance.

1. Introduction

For decades, safety advancements in aviation have been achieved, at least in part, through improvements in aircraft systems technology and automation. In contrast, these same factors have been pointed as contributing factors in some aviation accidents. The increasing automation and complexity in aircraft systems may present a considerable challenge to flight crews all over the world. Along with this modernization, concerns related to human machine interface are raised. In an unexpected or non-normal event, mainly in high workload circumstances, it is not uncommon to emerge problems in decision-making related to interaction with complex aircraft systems, such as loss of situational awareness, over-reliance, lack of vigilance, misprogramming, etc. All these aspects may be affected by human performance variability into a stressful situation and potentially lead to an accident. This paper proposes use the Functional Resonance Analysis Method (FRAM) as a valuable tool in supporting safety analysis in sociotechnical systems to reconstruct an event scenario to bring clear comprehension in the everyday performance adjustments and to allow characterize the main points where the variability of human performance, in a given specific situation, could lead to an observed negative result. In this way, the main points could be monitored and damped aiming to anticipate and prevent future occurrences. In addition, this paper also proposes the application of the Perceptual Cycle Model (PCM) in the analysis of naturalistic decision-making coupled to the FRAM model.

The PCM usage highlights the behaviour and course of actions given an information received and schema at a specific moment. A case study is presented applying the FRAM together with PCM to model aspects of an accident. On July 17th, 2007, the Airbus 320 of TAM Airlines, operating as flight JJ3054 destined to *Congonhas* Airport in São Paulo, Brazil, lost control on the ground and overran the runway, colliding with a building and a fuel service station. All the 187 people onboard perished along with 12 fatalities on the ground among the people in the building. This crash became the deadliest aviation accident in Brazil history at that time. The probable cause was associated to one of the thrust levers not to be moved back to idle position, leading to ground spoilers not to be deployed and also the auto-brake not to be activated during landing. Once again in aviation, human factors appeared playing an important role in the sequence of events which, in this case, prevented the aircraft to properly decelerate, culminating in the runway excursion. However, human error should not be considered the cause of an accident, but rather the symptom of complex system weakness.

Several methods for accident investigations are available, such as ATSB (2007), ATSB (2015), CHIEF (2020), NSIA (2021), among others. However, the objective of this study is to explore the systemic method, FRAM together with aspects of naturalistic decision-making incorporated in the PCM method. The approach presented in this article can be incorporated to these mentioned methods.

2. Overview

The model in this article presented through the case study, also incorporates elements of predecessors occurrences, which were also present in the Brazilian accident. Several aspects related to this tragic event, such as the procedure to operate the thrust levers with one thrust reverser inoperative, runway pavement conditions, flight crew indications and warnings were discussed in this study.

2.1.*TAM JJ3054 Accident summary*

The flight departed from *Porto Alegre*, Brazil, at 17h19min, local time with 2.4 tons of exceeding fuel in relation to the minimum fuel necessary for the operation, on account of a practice adopted by the company at certain airports, and which is known as ‘tankering’, meaning that the aircraft received more than the fuel necessary and prescribed, taking advantage of a lower price. The aircraft was dispatched with one of the thrust reversers inoperative (thrust reverser on right side), as allowed by the Minimum Equipment List (MEL) [Cenipa, 2009].

The landing at *Congonhas* airport (*São Paulo*, Brazil) occurred at 18h54min. During the landing, the pilot supposedly left one of the thrust levers (thrust levers associated to the right-side engine) in “CLIMB” (CL) position. As consequence, the ground spoilers did not deploy, the auto-brake did not activate and the aircraft overran the runway, crossed over Washington Luís Avenue and hit a fuel service station and the air cargo service building of the very operator [Cenipa 2009].

2.2.*Systems description*

To better understand this event, we have to first explain the basic technical concepts of the systems involved in this occurrence.

2.2.1.*Thrust reversers*

The engine thrust reversers are devices that reverse the engine air flow and produce a thrust force contrary to normal operation, which contributes to aircraft deceleration.

To activate the reversers on landing, it is necessary that the aircraft be on the ground and that the thrust levers be moved back to “REV” position.

2.2.2.*Auto-brake*

The auto-brake is the system that automatically commands the aircraft brake system. For its operation, it is first necessary to arm it, selecting the braking intensity through the pushbuttons (LO, MED, MAX) on the auto-brake panel in addition to leave the selector switch “A/SKID & NW STRG” in the “ON” position. Once the ground spoilers are deployed, the auto-brake is then activated [aviation safety council, 2006].

2.2.3.*Ground spoilers*

Ground spoilers are aerodynamic surfaces that are activated (opened) during landing roll in order to increase drag and consequently result in increased braking performance of the aircraft. To activate the ground spoilers, it is necessary to arm the system with the speed brake lever in "ARM" position and move the thrust levers to the "IDLE" or "REV" position. Once the aircraft is on the ground, the ground spoilers are activated to open [aviation safety council, 2006].

2.2.4.*Thrust levers operation on landing*

In this model of aircraft (A320), throughout the flight, the thrust levers generally are kept in the "CL" (climb) position. On final approach, the flight crew receive an aural warning of 50ft, 40ft, 30ft, 20ft and then they receive the aural warning of "RETARD, RETARD". At this point, the pilots should move back **BOTH** thrust levers from "CL" position to "IDLE". And then, to activate the reversers, they should also move back **BOTH** thrust levers to "REV".

However, when an aircraft is dispatched with one thrust reverser deactivated according to MEL, the old procedure, that is, until 2007, was to move back **BOTH** thrust levers do "IDLE" (when receive the aural warning "RETARD, RETARD") and then move back to "REV" only **ONE** thrust lever, i.e., only the thrust lever associated to the operating thrust reverser [Cenipa, 2009].

2.3.*Contextual conditions*

As mentioned above, the main braking devices of the aircraft depend on the logic related to the thrust levers position during landing phase. In the accident discussed in this study, one of the thrust levers was left in the "CL" position, and consequently, both auto-brake and the ground spoilers did not activate.

This scenario was very stressed during the accident investigation, debating how an experienced pilot would leave one of the thrust levers in the "CL" position, since moving back only one of the thrust levers would supposedly be counterintuitive during landing. However, not everyone knows that, in fact, some events similar to TAM JJ3054 had already occurred, but that differently to this one, the pilots survived, in addition to the fact that the thrust levers assembly was intact for later analysis, demonstrating that there had been no thrust levers system failure.

2.3.1.*Predecessors*

On March 22, 1998, (Philippine Airlines flight PR137) and on October 18, 2004, (Taiwan, TransAsia Aiways flight GE536) there were runway overran of an A320. In both cases, one reverser was dispatched inoperative according to MEL and during the landing one thrust lever was left in the "CL" position, leading to the ground spoilers not deploy and the auto-brake not activate. In the first case, the accident analysis, identification of contributing factors and safety recommendation were very superficial, practically blaming pilots and recommending only more training. No safety recommendations were done regarding aircraft procedures or systems [Civil aeronautics board, 2000]. But in the second case, the investigation authority went deeper into human factor and operational issues, thereby identifying contributing factors related to the project that had not previously been identified. In this investigation, it was found that when the pilot moved back to "REV" the thrust lever associated to the operative reverser, the aural warning "RETARD, RETARD" ceased. The aural warning basically serves to alert the flight crew that they should reduce both thrust levers to "IDLE". However, during this accident, even with an incorrect thrust lever position (one thrust lever in "REV" while the other in "CL"), this aural warning stopped sounding, possibly giving a false impression that the thrust levers were at the correct configuration. Because of this, the investigation authority issued a safety recommendation to Airbus to review the design to ensure that the warning continue until both thrust levers be reduced to the "IDLE" position. In response, Airbus issued a modification to operators implementing a new warning message "ENG 1(2) THR LEVER ABV IDLE" being triggered during landing in a situation where one of the thrust levers is above the "IDLE" position while the other is in the "REV" position. This modification was not considered mandatory (through an Airworthiness Directive) by the certification authority, and at that time, TAM

(Airline) did not incorporate this modification. [aviation safety council, 2006].

Another important modification issued by the aircraft manufacturer was the revision of the landing procedure (thrust levers operation) when the engine thrust reverser is deactivated according to the Minimum Equipment List (MEL). As already mentioned, when there is an inoperative reverser (according to MEL), the old procedure was to move back **BOTH** thrust levers to "IDLE" (after receiving the aural warning "RETARD, RETARD") and then move back only **ONE** thrust lever (only the thrust lever associated to the operative reverser) to "REV". Now, the revised procedure would be to move back **BOTH** thrust levers to "IDLE" (after receiving the aural warning "RETARD, RETARD") and then also move back **BOTH** thrust levers to "REV". However, this new procedure increases 55 meters in the required landing distance for contaminated runway [Cenipa, 2009].

2.3.2.*Congonhas airport and flight JJ3054*

It is possible to say that the conditions at *Congonhas* airport and specifically TAM flight JJ3054 had a great influence on the sequence of events. In the first semester of 2007, both *Congonhas* runways underwent pavement recovery after a history of aquaplaning and were then released for operation on 29/Jun/2007, but without the implantation of the grooving.

Since the runway return to operation (29/Jun/2007) until 14/Jul/2007, no significant precipitation had been registered, with the operation occurring practically as dry runway. On July 15, 16 and 17, 2007 *Congonhas* returned to operate in the rain, with several reports of slippery runway being registered by different flight crew, including a specific one case of accident (aquaplaning on the main runway) of a regular transport aircraft – ATR-42-300 – flight PTN4763 one day before JJ3054 accident. Between 17h07min and 17h20min local time (17/Jul/2007) the airport runway was closed for inspection by the airport authorities. Thus, 5 minutes after flight JJ3054 takeoff, during the flight crew first contact with air traffic controller (ATC), the crew was informed that *Congonhas* was impracticable, with a wet and slippery runway. At 18h03min, flight JJ3054 received information from ATC that Congonhas airport had returned the normal operation. It is important to emphasize here, that during this period, the flight crew had to consider divert to another airport (*Guarulhos* international airport) for the landing moment, but that was not necessary afterwards. During the approach to São Paulo (Flight Level – FL – 100) the pilot asks to co-pilot to confirm *Congonhas* airport conditions, reminding him that they only had one engine thrust reverser operative. For several times, until landing, the flight crew and ATC mention the "wet and slippery" runway conditions.

It is observed that the operation at *Congonhas* airport may have represented a huge cause of concern based on the scenario developed (wet and slippery runway, occurrences reported in the previous day, one reverser inoperative according to MEL, etc). Additionally, the pilot was probably aware of the consequences of the revised procedure mentioned above (increase of 55 meters in the required landing distance). Thus, it is reasonable imagine that the pilot could have a predisposition to execute the old procedure intentionally, considering that *Congonhas* runway could be contaminated, in order to obtain a better aircraft deceleration performance upon landing roll, avoiding the 55 meters increase mentioned in the MEL. Such old procedure, although more efficient in terms of braking aspects, may end up inducing the flight crew to make mistakes, being recorded several occurrences where there was the incorrect positioning of the thrust levers. Then, dealing with all pressure caused by these circumstances, the pilot may have tunnelled his attention to the need of moving only the thrust lever (associate to the left engine thrust reverser) to "REV" position and in an error of perception, he have commanded only that thrust lever to the "IDLE position, leaving the other thrust lever in "CL" position. This condition can be seen in the flight recorder information. The left engine thrust lever moves from "CL" to "IDLE" and then from "IDLE to "REV" on landing touchdown, while the right engine thrust lever remains in the "CL" position the whole time until the end of recording. As previously mentioned, once one of the thrust levers is left in the "CL" position, the ground spoilers do not deploy on landing and consequently the auto-brake is not activated [black box, 2007].

Throughout the investigation, despite what was prescribed in the MEL, some pilots stated that they would choose to apply a procedure that was no longer in force, just because they considered it better (preventing the additional increase of 55 meters in the landing distance). In addition, according to the investigation report, regarding what was found in interviews and field researches, the operation conditions at *Congonhas* caused a widespread feeling of discomfort among the pilots. In accordance with those interviewed, that airport offered little or no margin for errors or failures. It is possible to identify that the influence of the runway conditions on the pilots, from a psychological perspective, favoured the creation of a state of anxiety. Following this line of reasoning, the lack of deceleration expected after landing could have been attributed by the pilots to the runway conditions. Without a correct understanding of the aircraft behaviour, they may have been led to believe that the aircraft was aquaplaning [Cenipa, 2009].

Also, it is important to comment on the "RETARD" aural warning. This aural occurs at the landing moment, when the aircraft is crossing 20ft above the runway and then, it is cancelled when the pilot performs the movement reducing both thrust levers to "IDLE". As this phenomenon is repeated in all landing operations, it is conceivable that this exposure ends up conditioning the pilots to understand that the cancelation of the "RETARD" aural warning means that both thrust levers are in "IDLE". However, it was also observed that when one thrust lever was positioned at "REV" and the other at "CL", the warning "RETARD" is deactivated by the system and could induce the pilots to believe, mistakenly, that both thrust levers would be in the correct configuration (both at "IDLE"). It is important to emphasize that during flight JJ3054, the aural warning did not comply with the function for which it was designed since it stopped sounding when one thrust lever was at "REV" and the other was at "CL" (wrong configuration) [Cenipa, 2009].

3. FRAM application

The Functional Resonance Analysis Model (FRAM) presents a methodical and systematic approach for identifying the variability in the behaviour of individual functions within complex systems, such as aircraft operation. Such variabilities or the combination of some of them can cause accidents or incidents [Hollnagel, 2012].

FRAM is based on four main principles: the principle of equivalence of successes and failures; principle of approximate adjustments; principle of emergency; principle of functional resonance [Hollnagel et al., 2008]

The FRAM analysis purpose is to identify how the system should have performed for everything succeed and to understand variability of functions that individually or in combination prevented this from happening. This is typically the variability that existed in the situation being analysed or could possibly exist under other conditions. A FRAM model describes functions of a system and the potential couplings between functions [Hollnagel, 2012]. To elaborate the FRAM model is recommended the following steps:

- Define the objective of the modelling.
- Identify and describe the essential functions of the system and characterize each function using the six aspects (Input, Output, Preconditions, Resources, Time, Control. It is also possible to graphically use a hexagon to represent each function);
- Characterize the potential variability of functions in the FRAM model.
- Determine the possibility of functional resonance based on dependencies or couplings between functions.
- Develop recommendations on how to monitor and manage variability.

Based on the information above, the variability of human performance occurs mainly in the function of "operate thrust lever for landing", in which an omission causing part of the procedure not be executed will impact the sequence variability (execution of the procedure) and may lead to adverse outcomes in the end. This was observed in the event of flight JJ3054, in which one of the thrust levers was left in "CL" and, as consequence, several braking devices were not activated on ground.

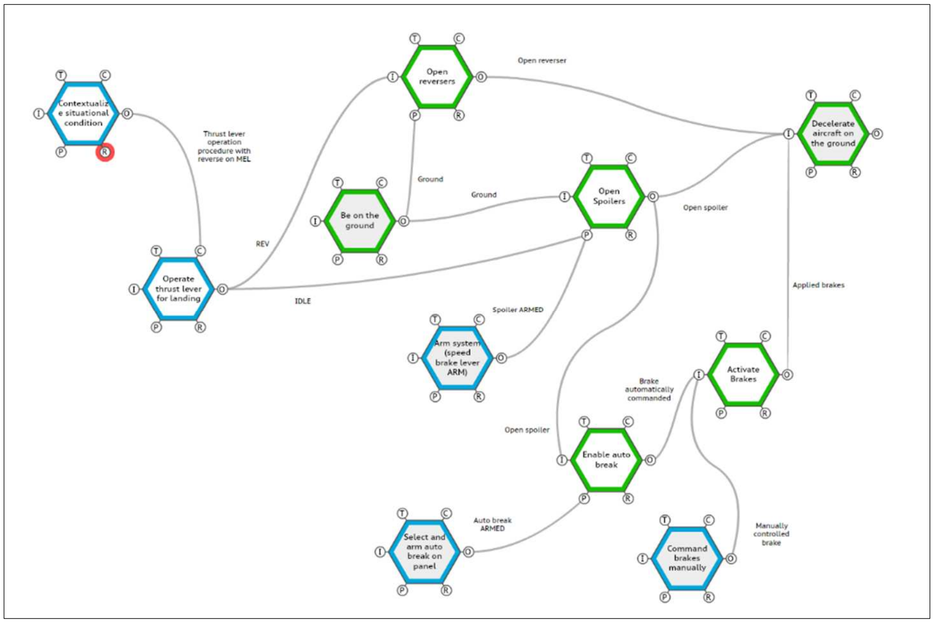

Fig.1 – Model created in the FRAM Model Visualiser

Possible causes affecting the human performance variability may be:

- Number of operating reversers (in this case, one inoperative reverser for 4 days).
- Weather condition (rain condition at destination airport).
- Runway condition information (wet runway, several reports of slippery runway, accident the day before due to aquaplaning, absence of grooving on runway pavement).
- Fuel quantity information (2,4tons more than minimum required due to tankering).
- “RETARD” alert (aural warning cancelled even with incorrect position of thrust levers).
- Crew experience (co-pilot with only approximately 200 hours in this aircraft model and hired as captain but operating as first officer).
- Applied service bulletins (there was a modification that could trigger a warning message of incorrect thrust lever configuration, but it was not incorporated by the airline).
- Thrust lever operation procedure with reverser on MEL (the fact that there was an old procedure known by pilots that reduced the required landing distance, lack of adherence to the most current procedure).
- Indication of thrust lever position correlated to engine power (Airbus auto-thrust philosophy that does not provide visual feedback through thrust levers movement correlated to engine power).

The items mentioned above were considered as “resources” of the function “contextualize situational condition”.

As countermeasures for the identified risks, we can list:

- Ensure that the characteristics of the runway pavement meet the all the requirements to ensure operational safety in case of rain.
- Establish parameters for “tankering” when operating in limit conditions of envelop.
- Modification of the “RETARD” aural warning system to perform the functional for which it was designed, that is, to alert the flight crew to position the thrust levers in the “IDLE” and do not stop sounding in a wrong configuration.

- Establish procedures for acting when the spoiler is not deployed and provide simulator training even considering a possible *go-around.*
- Ensure the implementation of the most safety-relevant service bulletins for the aircraft.
- Review communication process and compliance with the current procedure on MEL which describe the operation of thrust levers with inoperative reverser. Recorded flight data can be used (as used in FOQA – Flight Operations Quality Assurance) to analyse flight crew adherence to procedures.
- Ensure visual feedback for the flight crew correlating the position of the thrust lever with the engine power.
- Modification of the thrust levers logic to consider the clear intention of the crew to land and ensure the deceleration effectiveness, even with wrong positioning.

4. Naturalistic decision making process

The naturalistic decision making (NDM) framework emerged as a manner to study how people make decisions and perform cognitively complex functions in demanding real-world situations. This includes situations characterized by limited time, uncertainty, high risk, organizational and team restrictions, unstable conditions and variables amounts of experience [Neisser, 1976].

One of the models used in the analysis of the naturalistic decisions making process in the Perceptual Cycle Model (PCM). Basically, this model consists of three main steps that run cyclically. One step would refer to the information provided by the **world** (W) and environment. It represents all information available to the individual. The other step would be the **schema** (S), that is, the mental representation that a person has, based on the information this person received from the world. In sequence, a third step would be the possible **actions** (A) taken resulting from the individual schema [Plant and Stanton, 2013a, 2013b].

We can imagine that, in the FRAM model presented above, inside the "operate thrust lever for landing" function, there is this PCM structure running in the flight crew mind and being responsible for the human performance variability, which can cause different outputs from this function.

Based on the entire context of predecessor events, runway condition at *Congonhas* airport and the situation on flight JJ3054 itself, we applied this Perceptual Cycle Model and obtained the following result:

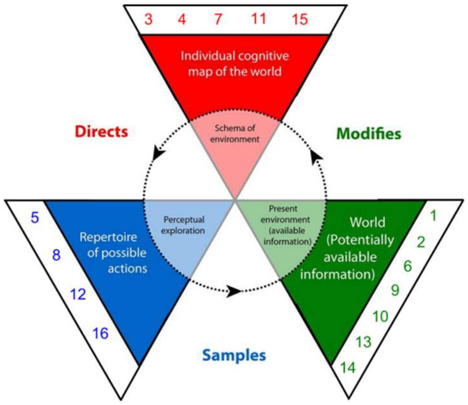

Fig.2 – PCM application on case study JJ3054 [source: Plant, Stanton, 2015 – CC BY-NC-ND 4.0, adapted].

1 – Previous reports of wet and slippery runway at *Congonhas* (W).

2 – Right side reverser inoperative according to MEL (W).

3 – Operation in Congonhas has little or no margin for errors or failures (S).

4 – Current procedure with one reverser inoperative according to MEL increases required landing distance (S).

5 – Execute the old procedure of not moving back the thrust lever (associated to the inoperative reverser) to "REV" (A)

6 – Aural warning "RETARD" is deactivated (W).

7 – Thought (incorrect) that the thrust levers positioning is adequate (S).

8 – Wait/monitor for the auto-brake and spoilers activation (A).

9 – Aircraft speed is still high (W).

10 – No fault messages received (W).

11 – Aircraft is not decelerating – wet and slippery runway – hypothesis (incorrect) of possible aquaplaning (S).

12 – Flight crew started to manually apply brake pedal after 6 seconds from touchdown (A).

13 – Aircraft speed is still high (W).

14 – No fault messages received (W).

15 – Aircraft is not decelerating – wet and slippery runway – hypothesis (incorrect) of possible aquaplaning (S).

16 – Application o manual brake (maximum deflection) after another 5 seconds (11 seconds from touchdown).

Final result: Poor deceleration performance – runway end – aircraft speed around 100 knots.

5. Conclusion

The accident of TAM flight JJ3054 provoked an impact in aviation worldwide and mainly in Brazil. It was highlighted several elements present in the occurrence context, that contributed to initiate the sequence of events resulting in the death of 199 people. The development of this present study allowed an analysis of the functions directly linked to the JJ3054 accident and may have help to better understand the complete scenario. In addition, it also allowed to visualize how qualitative analysis can help to investigate variability present in the scenario and thus, making it possible to create barriers to avoid possible risks.

This study also proposed an application of the Perceptual Cycle Model from Naturalistic decision making coupled to the developed FRAM model. An important FRAM function modelled in this accident was the thrust levers operation for landing, which is highly affected by human performance. The PCM usage highlighted the flight crew behaviour and course of actions operating the thrust levers given the information received and the pilots schema at that moment. With the understanding obtained from the PCM application, it is possible to feed back the FRAM model improving the comprehension of the accident scenario and key points affecting the human performance variability, enabling manage it. The joint application of FRAM and PCM proved to be a great contribution to accident prevention and the engineering of more resilient complex dynamic sociotechnical systems.

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