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Application of causal analysis based on systems theory (CAST) to regulatory decision-making: A case study of the Sikorsky S92A

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ABSTRACT

Ensuring aviation safety requires maintaining the integrity of product design and operations. The Federal Aviation Administration (FAA) regulates Transport Category rotorcraft design through 14 CFR Part 29, establishing Categories A and B of certification for multiengine rotorcraft, and requires aircraft to be operated according to the certified procedures in flight manuals. This paper presents a case study of the Sikorsky S92A, a Transport Category rotorcraft that is not certified for elevated helideck operations according to Part 29, but operates primarily in the offshore market through FAA-authorized exemptions from applicable regulation. To understand how this discrepancy between the aircraft's certification and operation came to be, a relatively new accident analysis methodology called Casual Analysis based on Systems Theory (CAST) is applied to a hypothetical accident involving an S92A, strongly based on a real incident described in a service difficulty report. The CAST results identify unsafe decisions on the part of flight crews, air operators, the aircraft manufacturer, and the FAA that contribute to the accident. We explain these contributions by identifying several systemic factors generalizable to the entire offshore rotorcraft industry that underlie unsafe decisions, and we propose a set of recommendations to address them.

1. Introduction

The main goal of any national Civil Aviation Authority is ensuring aviation safety. In line with this, the Federal Aviation Administration's (FAA) mission includes *"the issuance and enforcement of regulations and standards related to the manufacture, operation, certification and maintenance of aircraft."* [1].

From a regulatory perspective, in order to achieve aviation safety two pillars are essential: product integrity and operational integrity. Product integrity involves design, certification, production, and quality assurance, among other factors, while integrity of operations involves but is not restricted to flight operations, crew training, minimum equipment lists, standard operating procedures, and ensuring continued airworthiness. There is an intrinsic relationship between product integrity and operational integrity that must be maintained in order to achieve continuous operational safety and, thereby, aviation safety as a whole [2] (Fig. 1).

The International Civil Aviation Organization (ICAO) publishes Standards and Recommended Practices (SARPs) for different subject areas within aviation. SARPs are published by ICAO through 19 Annexes and are subject to regular amendments. In Annex 19, ICAO defines safety as "*the state in which risks associated with aviation activities, related to, or in direct support of the operation of aircraft, are reduced and controlled to an acceptable level*" [4].

Some regulations regarding rotorcraft certification and operation are applied before leaving the Original Equipment Manufacturer (OEM) gate (i.e., factory gate in), while other regulations are applied after the rotorcraft leaves the OEM's gate (i.e., factory gate out). Some additional regulations are applied on both sides of the OEM's gate. The relationship between ICAO Annexes and FAA regulations on both sides of the OEM's

Abbreviations: AC, Advisory circular; CAST, Causal analysis based on systems theory; CFR, Code of federal regulations; EASA, European union aviation safety agency; FAA, Federal aviation administration; FSB, Flight standardization Board; FSI, Flight safety international; ICAO, International civil aviation organization; IOGP, International association of oil & gas producers; MTOW, Maximum takeoff weight; OEM, Original equipment manufacturer; PC, Performance Class; RFM, Rotorcraft flight manual; SARP, Standard and recommended practice; STAMP, System-theoretic accident model and processes; STPA, System theoretic process analysis; TCDS, Type certificate data sheet; TDP, Takeoff decision point.

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gate is presented in Fig. 2.

Helicopters are essential for supporting offshore oil and gas activities worldwide [5]. According to the International Association of Oil & Gas Producers (IOGP) [6], about 300,000 rotorcraft flight hours were registered across IOGP's members in 2022. This is a downgrade from the over 400,000 flight hours in 2019, mainly as a result of the COVID-19 pandemic, but this still accounts for the transportation of over 3.4 million passengers annually.

Since a 2016 accident involving an Airbus H225/EC225 helicopter in the North Sea, the 19-passenger Sikorsky S92A [7] has dominated offshore air operations in the western hemisphere. In January 2016 there were seventeen Airbus H225/EC225 and fifteen Sikorsky S92A in Brazilian offshore operations, while by February 2023 there was only one Airbus H225/EC225 and thirty-three Sikorsky S92A [8]. As seen in Fig. 3, in 2018 the S92 had the highest number of reported flight hours in offshore operation, as collected and reported by HeliOffshore [9].

Typically, an offshore flight consists of one takeoff or landing on land and one or more takeoffs or landings on oil rigs. This means that at least 50% of all offshore takeoff and landing operations occur on elevated helidecks. Most offshore helicopter operations involve the transportation of workers, so disruptions can lead to discontinuities in production flows that can have severe social, economic and political impacts [5]. Though offshore helicopter operations generally pose higher risks than ground-based operations, statistical analyses regarding the safety of the offshore helicopter industry have shown lower accident rates in offshore operations, as a result of stricter regulation and tighter control both on the design and operational sides [10]. However, the offshore industry is not immune to safety concerns, and to ensure both product and operational integrity in the industry, it is essential that the environment in which these helicopters operate match the basis on which they were certified.

This study demonstrates an application of an accident analysis methodology called Causal Analysis based on Systems Theory (CAST) to a near miss involving the S92A, to model and understand a gap between the certification and operation of that helicopter in the offshore market. CAST is used to examine how interactions between flight crews, air operators, OEMs, and regulatory authorities allow the S92A to occasionally operate in environments in which it is exposed to a higher likelihood of a catastrophic loss than is widely known and disseminated. The CAST findings are then used to propose recommendations for improving regulatory decision-making and offshore helicopter operations as a whole.

The remainder of this paper is structured as follows: Section 2 outlines a literature review of the fundamentals of certification and operational regulation of transport category rotorcraft, Section 3 presents a brief description of CAST; Section 4 presents a summary of the results of a CAST applied to a near miss involving the S92A; Section 5 analyses the gaps uncovered in the CAST more deeply and provides recommendations for improving the safety of offshore operations; and Section 6 concludes the paper.

2. Background and literature review

2.1. Fundamentals of airworthiness and operations regulation

2.1.1. Airworthiness certification regulation for transport category rotorcraft

ICAO defines an aircraft as airworthy *"when it conforms to its approved design and is in a condition for safe operation"*, establishing the airworthiness basis in Annex 8 – Airworthiness of Aircraft [11, p. 8].

In the USA, Title 14 of the Code of Federal Regulations (14 CFR) establishes all rules prescribed by the FAA to control aviation activities. The certification requirements regarding the design of Transport Category rotorcraft are set in 14 CFR Part 29 (Airworthiness Standards: Transport Category Rotorcraft) and are divided into Category A and Category B for multiengine rotorcraft. The requirements for Category A certification are more stringent than Category B [12].

According to the original version of 14 CFR Part 29, rotorcraft with a maximum takeoff weight (MTOW) greater than 20,000 lb had to be certified as Category A, while rotorcraft with a MTOW of 20,000 lb or less could be certified as Category B, as shown in Fig. 4(a).

Each certification category also possesses different operating limitations [12]. For example, to be certified as Category A, a rotorcraft must prove it is capable of continued safe flight with critical engine failure at any point during the flight path. Category B certification does not require the rotorcraft to be capable of taking off, continuing flight, or landing at the intended destination in the event of an engine failure. A rotorcraft certified to Category B is therefore assumed to perform an

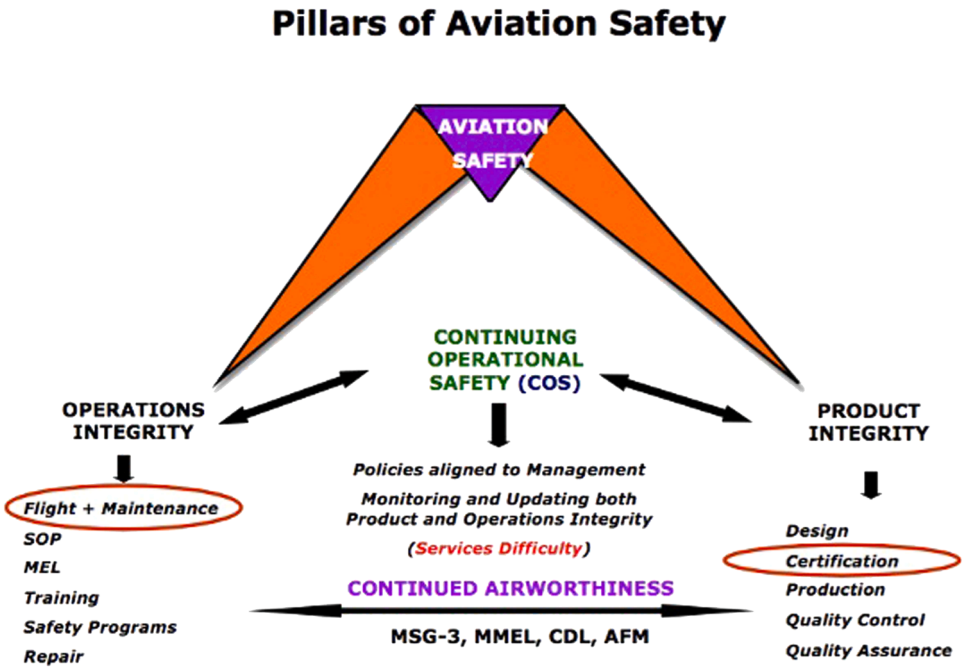


Fig. 1. Pillars of Aviation Safety [3].

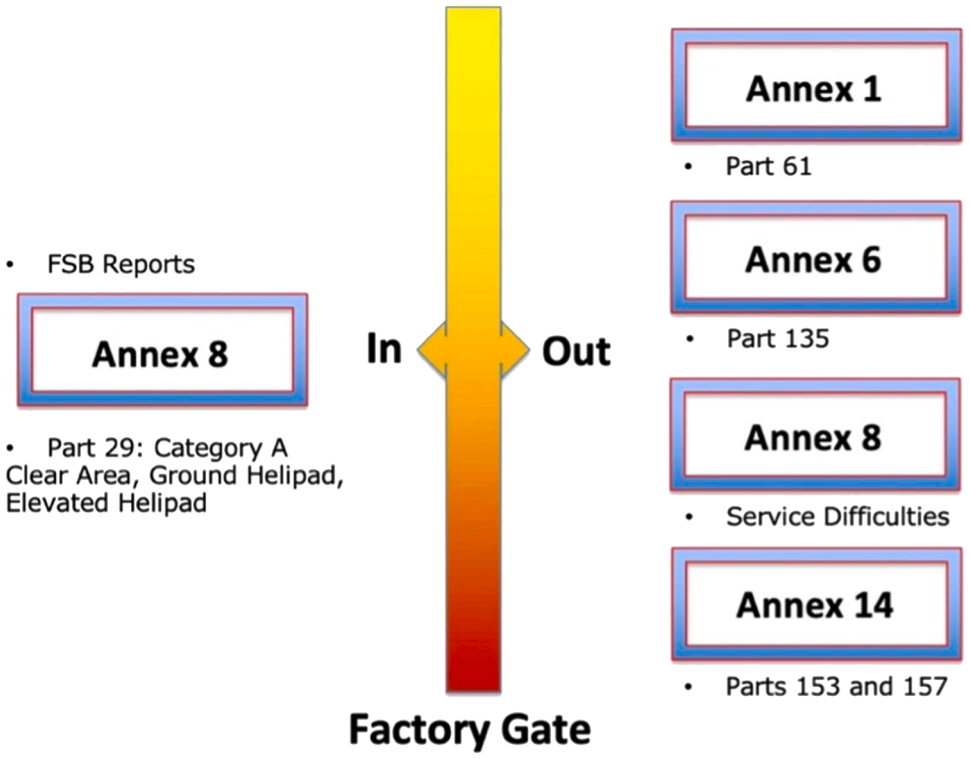


Fig. 2. ICAO Annexes and FAA regulations – Factory gate In/Out.

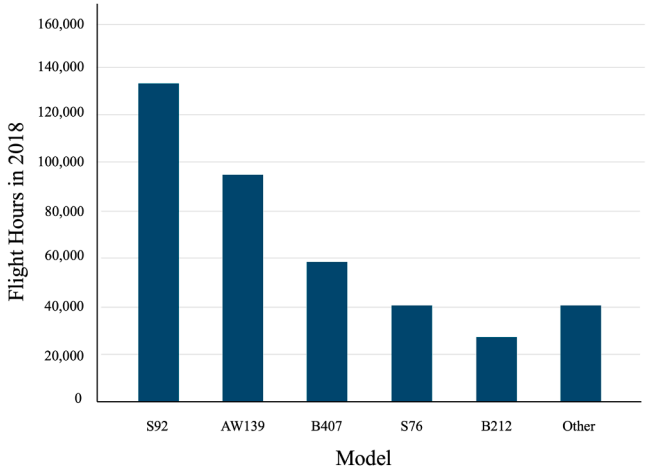


Fig. 3. Number of flight hours operated by each helicopter model in offshore operations, as collected and reported by HeliOffshore (adapted from [9]).

emergency forced landing if the critical engine fails at any point of the flightpath [2].

In 1983, the FAA published Amendment 29–21 to Part 29 [13]. This amendment removed the 20,000 lb weight limit for Category B and removed the HV envelope as an operating limitation for rotorcraft carrying up to 9 passengers. This change created, in practice, *three* certification categories for transport category rotorcraft with MTOW over 6,000 lb (revised to 7,000 lb in 1999): one pure Category A, one pure Category B, and one 'hybrid' Category [2], as can be seen in Fig. 4(b).

In the 'hybrid' category [2], rotorcraft capable of carrying 10 or more passengers and with a MTOW up to 20,000 lb must comply with all requirements of Category B certification and, additionally, the following two performance requirements of Category A certification:

- Part 29, §29.67(a)(2) – 2nd segment of Category A takeoff OEI, from 200 to 1000 ft above the surface, with rate of climb of 150ft/min at *Vy*; and
- Part 29, §§29.87 and 29.1517 – forbidden HV envelope, where any combination of height and forward velocity, including hover, within which it is not possible to make a safe landing following power failure of the critical engine.

Within Category A certification, there are also three different profiles for which a helicopter can be certified: clear area, ground heliport and elevated heliport. In the clear area profile, shown in Fig. 5, takeoff is typically horizontal. The takeoff decision point (TDP), that is, the point at which the takeoff can no longer be aborted, is usually defined in terms of indicated airspeed, as is typical for fixed-wing aircraft. In ground and elevated heliports, shown in Figs. 6 and 7 respectively, takeoff is typically vertical and the TDP is usually defined in terms of height over the takeoff surface. The main difference between ground and elevated heliports is that, in elevated heliports, the rotorcraft may descend below the level of the takeoff surface while attaining the takeoff safety speed (VTOSS) [12].

The reasons why operations over elevated helipads/helidecks are intrinsically more risky than over clear areas or ground helipads is due to the expected existence of obstacles in the vicinity and crosswind during takeoff/landings, particularly in offshore operations. Additionally, the helipad dimensions may be reduced down to the helicopter's d-value (maximum helicopter dimension). The TDP height may also be reduced to just 30 ft above the helideck surface, due to the risk of the pilot losing sight of the helideck and being unable to reject the takeoff in the event of one engine becoming inoperative. Every second of delay in the pilot's reaction to an OEI condition at the TDP may cause a reduction of 15 ft of helideck edge clearance distance [14]. The HeliOffshore report referenced earlier [9] also provides statistics around helicopter safety in offshore operations and a summary of documented accidents.

The FAA does not require specific practices to demonstrate that a helicopter complies with 14 CFR Part 29. However, as guidance for OEMs, the FAA does provide advisory circulars (ACs) that outline

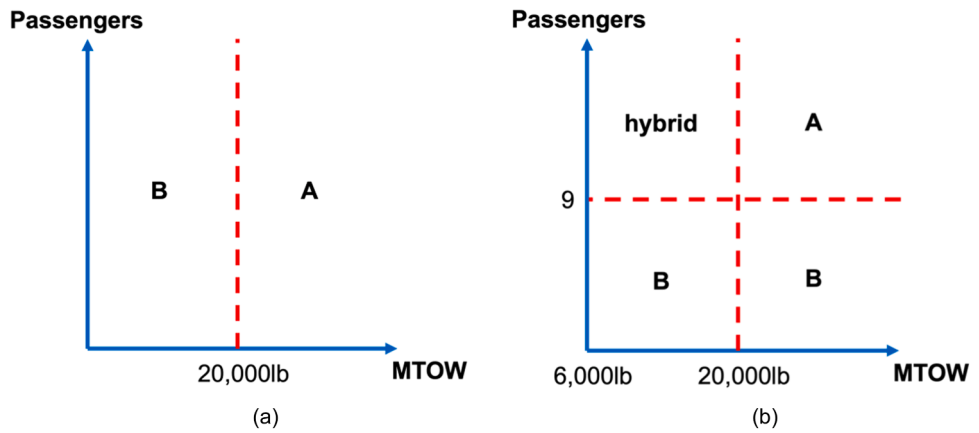


Fig. 4. (a)Original certification categories based on 14 CFR Part 29. (b) – Certification categories based on FAA Part 29 Amendment 29–21, item 29.1.

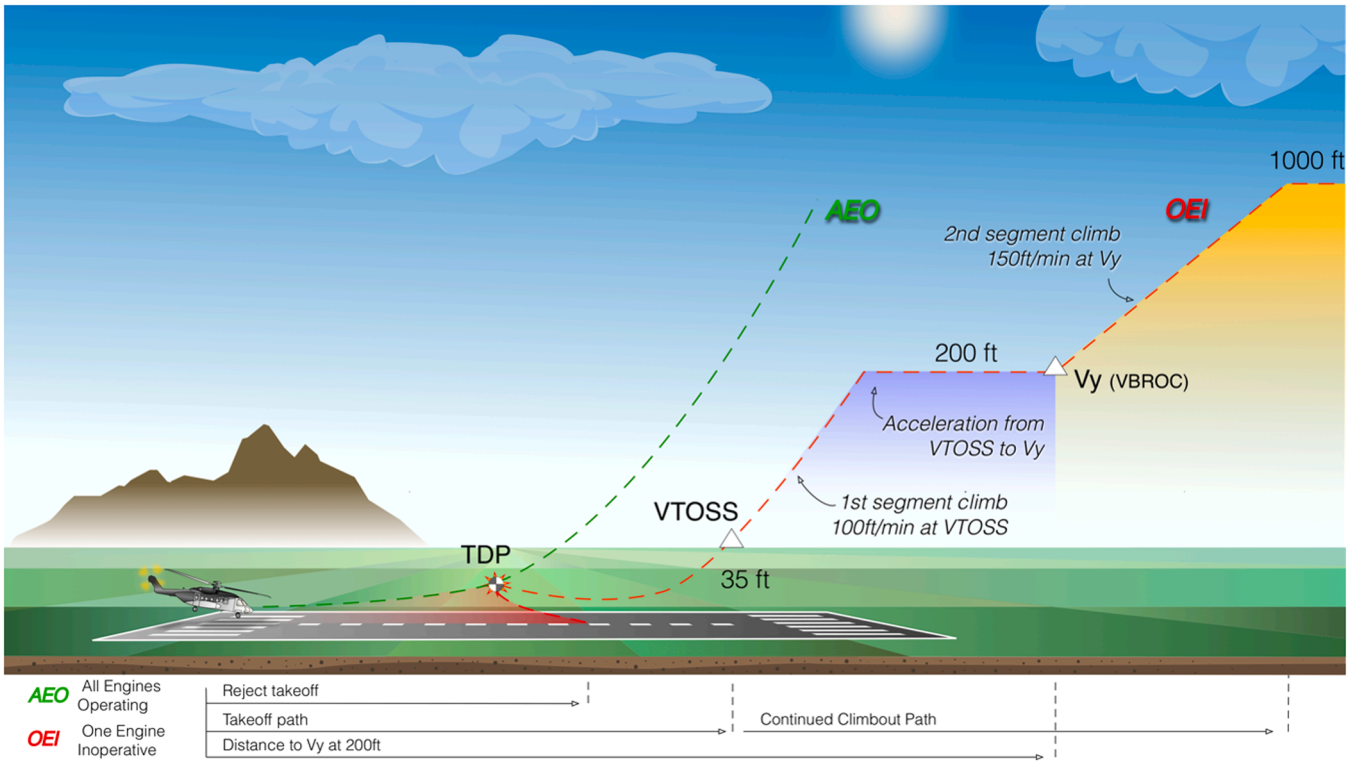


Fig. 5. FAA Part 29 Terminology – Category A Takeoff Profile (clear area).

acceptable means for showing compliance with particular regulatory criteria. FAA AC 29–2C, titled "Certification of Transport Category Rotorcraft" provides a recommended means of complying with 14 CFR Part 29 [15].

Additionally, for helicopters with a MTOW over 12,500 lb, the FAA also requires that pilots operating that helicopter obtain a "type rating", whose training requirements are established by a Flight Standardization Board (FSB) during the type certification process [16]. FAA AC 120–53B CHG1 (Guidance for Conducting and Use of Flight Standardization Board Evaluations) [17] provides an acceptable means of compliance for determining pilot training and qualification requirements for a particular aircraft. The FSB only establishes training requirements for the categories for which the helicopter has been certified.

2.1.2. *Operational regulation for transport category rotorcraft*

In 1986, ICAO published Annex 6 Part III, titled Operation of Aircraft – International Commercial Air Transport — Helicopters [18, p. 6]. That Annex states that every helicopter *"shall be operated in accordance with a code of performance established by the State of the Operator, in compliance with the applicable Standards of this chapter"* [19, p. 6]. This means that each individual country's civil aviation authority (CAA) is responsible for ensuring that rotorcraft in that country operate in accordance with a 'Code of Performance' established by the CAA.

To serve as a basis for the code of performance, Annex 6 Part III defines three 'Performance Classes', which are sets of rules that prescribe helicopter operational performance requirements when operating in each class. With one engine inoperative (OEI), the requirements for operating in Performance Class 1 (PC1) are equivalent to the certification requirements for Category A. The requirements for operating in Performance Class 2 (PC2) are equivalent to the certification requirements of the 'hybrid' Category certification, (i.e., Category B during takeoff/landings and Category A enroute and in the 2nd segment takeoff OEI). The requirements for operating in Performance Class 3 (PC3) are equivalent to the certification requirements for Category B in

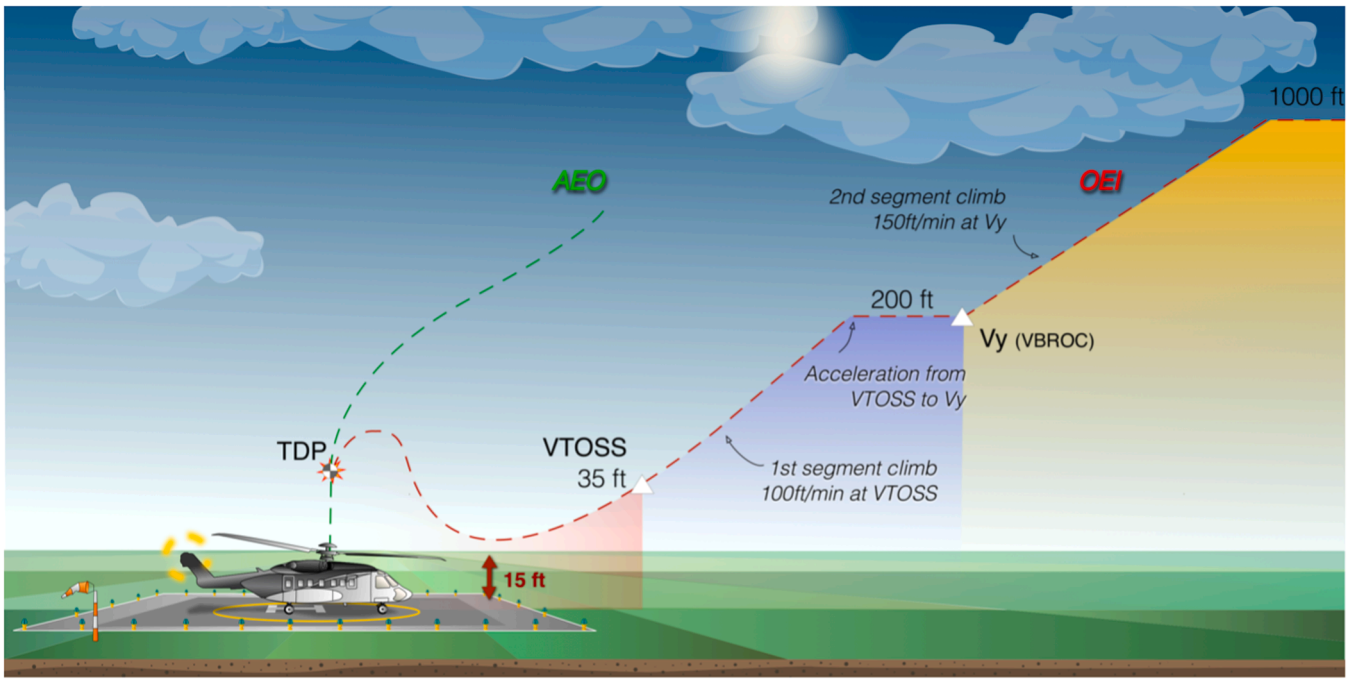


Fig. 6. FAA Part 29 Terminology – Category A Takeoff Profile (ground heliport).

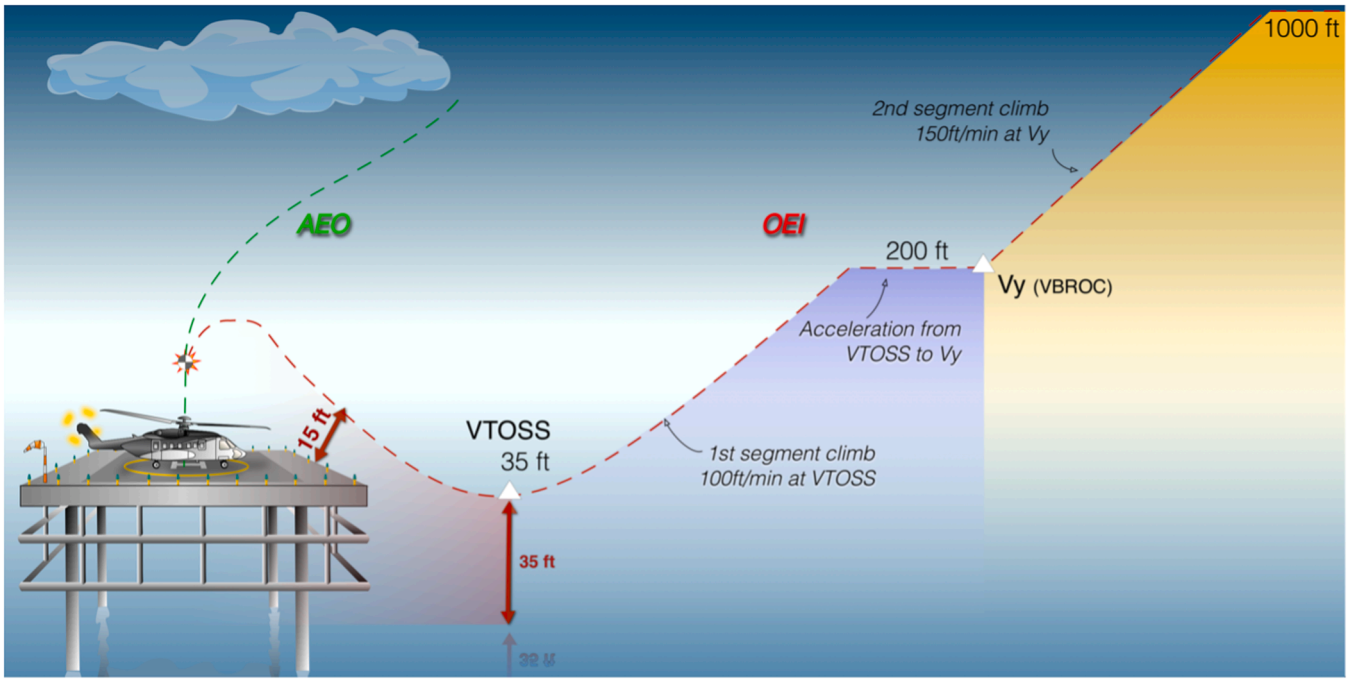


Fig. 7. FAA Part 29 Terminology – Category A Takeoff Profile (elevated heliport).

all phases of flight [2].

EASA adopted the Performance Classes as recommended in ICAO Annex 6 Part III, while the FAA declared differences to the annex and did not adopt the Performance Classes. In practical terms, for ICAO and EASA, a helicopter demonstrates its operational capability during certification, but is operated in accordance with a Code of Performance established by the country in which the operator is based [11,14]. For the FAA, a helicopter demonstrates its operational capability during certification, and must be operated in accordance with the certification parameters established in the rotorcraft flight manual (RFM) [2,16].

The applicable regulation that outlines the FAA's rules around the operation of rotorcraft is 14 CFR Part 91. In §91.9(a), the regulation states that *"no person may operate a civil aircraft without complying with the operating limitations specified in the approved Airplane or Rotorcraft Flight Manual"*. However, the FAA has, on occasion, authorized exceedances to the operating limitations set during certification and outlined in flight manuals. For example, in 1973, the FAA published 14 CFR Part 91, §91.31 (later renumbered to §91.9 (d)), which opened the possibility for Category A helicopters to make transient flights over water during offshore helideck takeoff and landing operations, through

what was originally a prohibited range of the helicopter's height-velocity (HV) envelope [20,21]. Additionally, without enacting new regulation, the FAA can also provide *exemptions* to §91.9(a), allowing individual operators to operate their rotorcraft beyond the limitations outlined in the flight manual.

2.2. The Gap between offshore helicopter certification and operations

Previous research on offshore helicopter operations in the oil and gas industry were mostly focused on operational safety [5,22], logistical improvements in transportation [23,24], and statistical analysis of accident data [25,26,27,28].

In a 2022 paper, Veras Neto and De Andrade [2] compared the certification and operation of Transport Category rotorcraft, first identifying a regulatory gap that exists for some helicopters primarily used in the oil and gas industry. That study found that a number of Transport Category rotorcraft operating in the offshore market, including the Sikorsky S92A and Airbus H225/EC225, are not certified to operate from elevated helidecks. The procedures for elevated helideck vertical take-off and landing presented in these helicopters' rotorcraft flight manual (RFM) are not certified or approved by the FAA [12] or EASA [29] under their relevant certification regulations. To allow the helicopters to operate in this regime, the FAA grants operators exemptions, as described in Section 2.1.2.

As a result, a helicopter operating from an elevated helideck at a takeoff or landing weight consistent with the MTOW for Performance Class 2 (PC2) would not actually be covered by the safety assurances provided by Category A certification. In reality, during each takeoff and landing from an elevated helideck in the event of the critical engine fails, for a period of up to 9 s after the TDP, the helicopter would be exposed to the possibility of a deck-edge strike, or an emergency forced landing with obstacles on the surface, rather than a safe flyaway as required by Category A or a safe forced landing (SFL) as required by Category B.

The CAST results presented in Section 4 of this article attempt to understand how this gap formed by examining one instance of a critical engine failure at takeoff involving a Sikorsky S92A.

3. Method

3.1. The stamp framework

The System Theoretic Accident Model and Processes (STAMP) is a framework for understanding accident causality that is underpinned by systems theory [30]. In STAMP, safety is viewed as an emergent property of complex systems, and the only way to prevent accidents is to enforce the appropriate *controls* on a system's behavior. These controls, typically termed *safety constraints*, can include physical controls like closing a valve, but they can also include organizational constraints like procedures and training. Knowing when and how to enforce these constraints requires appropriate information, termed *feedback*. The *feedback-control* loop is the basic unit of a system model in STAMP. Also, in STAMP, a system does not simply refer to a physical system like a landing gear or even a whole aircraft. In STAMP, a system includes operators, management, and even regulatory authorities that all have control over the behavior of the physical components.

3.2. Causal analysis based on systems theory (CAST)

Causal Analysis based on Systems Theory (CAST) [31] is an accident analysis technique based on the STAMP framework. A detailed overview of CAST is found in the CAST Handbook [31]. The goal of CAST is to provide a structured approach that guides experts to think in more depth about the causes of an accident and generate better recommendations to prevent similar accidents in the future. CAST can also be applied to near misses, or any undesired situation, even if no loss was actually incurred.

CAST differs from traditional accident analysis techniques as it does not seek to identify a single "root cause" for the accident. Instead, CAST models the system involved in the accident as a collection of feedback control loops (termed a *control structure*) and examines each individual *controller* to understand their contributions to the accident. Rather than stop at each contribution, though, CAST goes on to identify why it appeared reasonable for each controller to make the decisions they made, even if those decisions were unsafe in hindsight. CAST also does not assign blame for an accident to any component, individual, or organization within the system. Instead, it focuses on understanding why the safety constraints were not enforced appropriately and generating recommendations to ensure they are enforced in the future.

The five steps of CAST involve: (1) assembling the basic information about the accident; (2) modeling the system involved as a hierarchical control structure; (3) analyzing each controller for their contributions to the accident; (4) analyzing the control structure as a whole to identify systemic factors affecting the behavior of all controllers; and (5) creating an improvement plan to prevent future accidents. For brevity, the CAST example in this study will only summarize the results from steps 1, 2, 3 and 5.

4. Results

4.1. Summary of the case

The incident being examined using CAST in this study is based on a real incident that occurred on May 4th, 2015 and was documented in a Service Difficulty Report submitted to the FAA. The text of the report reads:

> "(CAN) NR 2 ENGINE FAILED WHILE IN THE HOVER, OVER THE RUNWAY, JUST PRIOR TO ROTATING FOR THE TAKEOFF. THE ACFT WAS LANDED. THE RT SEAT PILOT HEARD 2 QUICK POPS AND NOTICED THE TGT ON NR 2 RISE JUST PRIOR TO ENGINE FAILURE. THE WEATHER WAS SKY CLEAR WITH WINDS APPROXIMATELY 300 AT 10 KNOTS AND TEMPERATURE 13. THE ACFT WAS TAXIED BACK TO THE RAMP WITHOUT FURTHER INCIDENT."

The SDR indicates that this incident occurred in the FAA's southwest region (encompassing the states of Arkansas, Louisiana, Texas, Oklahoma, and New Mexico). The mention of a "ramp" in the narrative implies the incident did not occur in an elevated helideck environment, although it could have occurred in the 9 second window mentioned earlier, as it occurred during the hover checks that precede rotation for takeoff from clear areas. Additionally, there is little information on the number of passengers in the aircraft at the time of the incident, or its takeoff weight.

Fortunately, no catastrophic accident resulted from this sudden engine shutdown. However, in a scenario in which that same shutdown occurred up to 9 s after the TDP during a takeoff from an elevated helideck, in an aircraft at its full capacity of 21 occupants, the rapid loss of helideck edge clearance discussed earlier combined with crosswind and potential obstacles could lead to a higher reduction in safety margins. Based on the gap uncovered by Veras Neto and De Andrade as described in Section 2.2, that same shutdown in those conditions would result in a crash over the helideck, a crash over the sea following a tail strike on the helideck-edge, or a forced landing with low chances of survivability, if operating over hostile water conditions. Therefore, the CAST results presented in the next subsection will examine a hypothetical accident similar to the incident described in the SDR. In the hypothetical accident analyzed, the engine loss occurs up to 9 s after the TDP during a takeoff from an elevated helideck, leading to the catastrophic consequences described above.

It is important to note that, because the focus of this paper is on the regulatory gap, the focus will be on the decision-making at the operator, OEM, and regulator levels, rather than on the technical causes of the engine shutdown. Those technical causes are outside the scope of this

analysis, though CAST could still be used to identify those causes if that were the focus of the study. Instead, our CAST aims to explain what kind of decision-making at the operator, OEM, and regulatory level could have led to a situation in which a reasonable flight crew operates an aircraft in an environment where a critical engine failure can lead to catastrophic consequences. Besides identifying the unsafe decisions, CAST also attempts to explain why those decisions may appear reasonable by examining mental model flaws and contextual factors surrounding them.

4.2. Summary of cast results

4.2.1. Basic information

The first step of CAST is assembling the basic information about the accident. As described above, the "accident" being analyzed here is a hypothetical situation based on the one described in the SDR above, but where a critical engine failure occurs during a takeoff from an elevated helideck. The system in this case is defined as the aircraft and its occupants (including the flight crew), the operator, the manufacturer, and the regulatory authorities that oversaw each step of the aircraft's certification and operation. The losses from this accident would include loss of life and destruction of the aircraft, and the system level hazards and safety constraints are:

System Hazard 1: Aircraft loses ability to remain airborne
Safety Constraints:

- Aircraft must have sufficient performance to remain airborne with critical engine inoperative
- Aircraft must be able to detect and recover from condition in which it does not have sufficient performance to remain airborne

System Hazard 2: Aircraft does not maintain adequate separation from outside objects

Safety Constraints:

- Aircraft must maintain adequate separation from outside objects
- Aircraft must be able to detect and recover from a violation of adequate separation

4.2.2. Safety control structure

The control structure that describes the system being examined is shown in Fig. 8 below. Because the chosen scope of this paper is the management and regulatory controls, the control structure abstracts away the details of the aircraft's physical systems, focusing instead on the system's certification and operation.

4.2.3. Role of each controller in the loss

The next steps of CAST require the analyst to examine how each controller in the control structure contributed to the accident. Each controller's unsafe decisions are explained by considering what mental model flaws and contextual factors made the unsafe decision appear

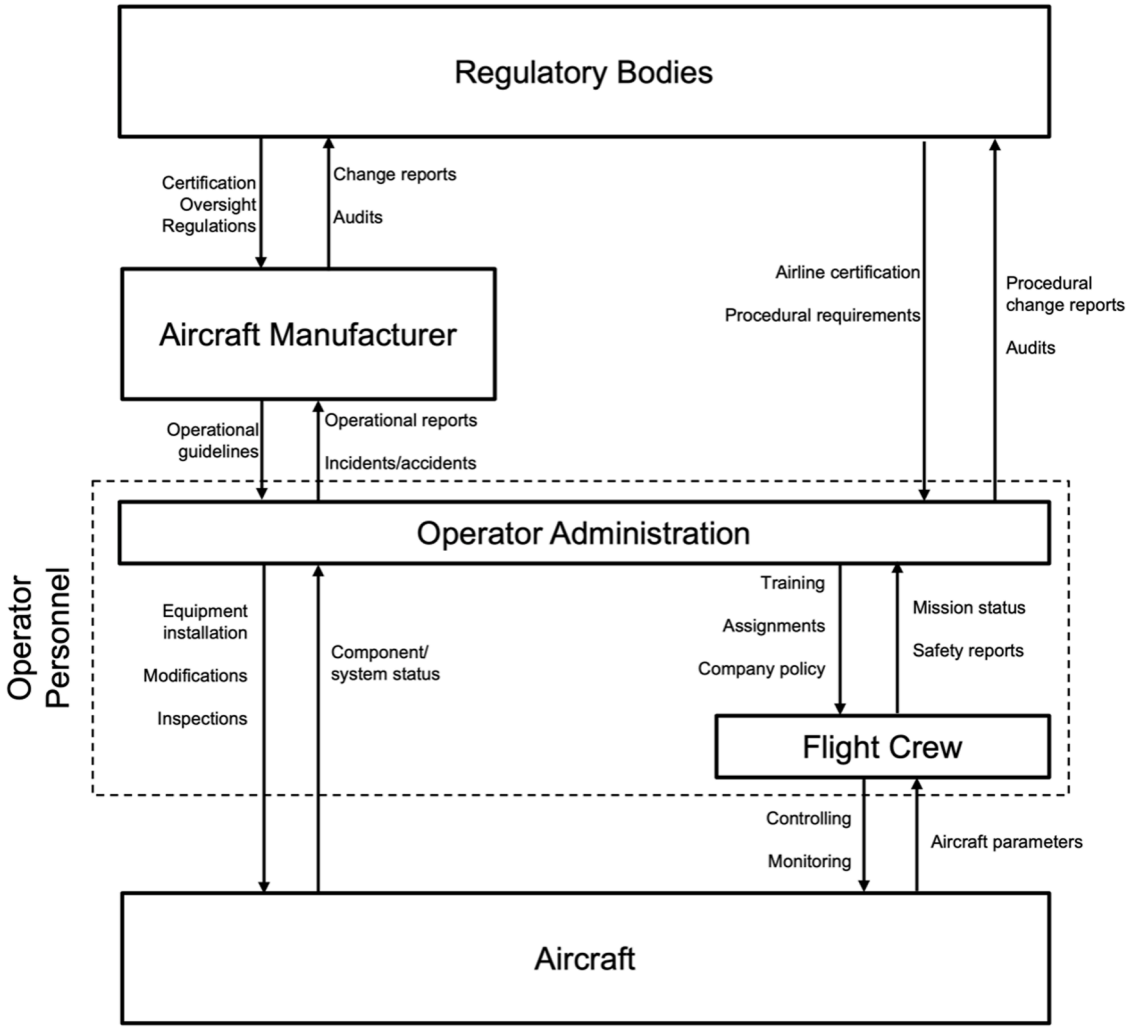


Fig. 8. Safety control structure.

reasonable. The analysis begins at the bottom of the control structure, with the contributions of the flight crew to the unsafe situation, followed by the contributions of the air operator, then the aircraft manufacturer, and then the regulatory authority. These contributions are outlined in Tables 1, 2, 3 and 4 respectively.

The information for this CAST analysis was obtained from prior works by one of the authors [2], as well as analysis of regulatory documentation that is publicly available. The contributions at each level of the control structure generated questions that drove the analysis towards the higher levels of the structure.

5. Discussion and recommendations

The CAST results provide interesting insights surrounding the specific case of the Sikorsky S92A helicopter, but closing the gap between certification and operation of transport category rotorcraft in general requires understanding the systemic factors that underlie the specific contributions identified above. Sections 5.1 through 5.5 explore some systemic factors uncovered by this CAST and present recommendations for addressing these factors more broadly. Section 5.6 discusses specific implications for the S92A from the CAST findings.

5.1. Flawed mental models from operators around certification

The decision to operate the S92A in an environment for which it was not certified (elevated helideck operations) can be seen as a contribution of both the flight crew and the operator to this loss, as seen in Tables 1 and 2. However, as other CAST analyses have shown, flawed decision-making at the operational level is not a root cause of accidents, but a symptom of broader systemic factors that affect how those decisions are made [32]. The mental model flaws and contextual factors that affected this decision could easily manifest themselves in other incidents and with other aircraft as well.

A 2023 study surveyed 54 out of the 205 pilots who hold valid S92A licenses in Brazil, and asked them: *"Is the helicopter you fly certified/approved for elevated helideck operations?"* All respondents answered "Yes" [33]. It is also possible that the management deciding on and planning elevated helideck missions held similar misunderstandings surrounding the certification of the aircraft. These mental model flaws raise questions about the information (feedback) that crews and operators have about the certification status of aircraft they operate, and point the analysis towards the aircraft manufacturer and regulatory authorities.

The information considered mandatory for a rotorcraft flight manual is prescribed in Part 29 regulations, and FAA AC 29–2C states clearly that the RFM section on "Operating Limitations" should list whether or not the aircraft is approved for Category A operations at ground and elevated heliports [15]. The Sikorsky S92A RFM, however, does *not* mention the different Category A profiles the helicopter has been certified to. Crews have to read >300 pages to discover that Part 1 of the RFM, which is the certified part of the manual, only presents Category A procedures for horizontal takeoff from airport runways and vertical takeoff from ground level helipads, with no mention of Category A procedures for elevated heliports.

On the other hand, Part 2 of the RFM, which is optional and uncertified [7], *does* present supplemental performance data for two vertical takeoff and landing procedures in elevated helidecks. These procedures, however, are never connected to the aircraft's certification status. Instead, the RFM Part 2 simply presents a statement that says *"The operators are responsible for obtaining operational approvals from their cognizant National Aviation Authority"* [34]. The main difference between both parts of the RFM is the absence of an explicit statement on the cover page of RFM Part 2 stating that its contents *are* certified by the FAA.

It would therefore not be surprising if flight crews and operators interpret the elevated helideck procedures as certified during type certification, but also requiring an additional operational approval (as is the case with performance-based navigation operations) rather than wholly uncertified. This misunderstanding can also be compounded by the fact that the introduction to RFM Part 2 presents a warning that states that *"failure to comply with the limitations and procedures in this Flight Manual, may result in damage to equipment, personal injury or loss of life"* [34] in the same way that Part 1 does, despite only Part 1 being certified.

Thus, in the lens of CAST, the unsafe control action on the part of the flight crews and operators could be explained by *missing* and *misleading* feedback. Ensuring that crucial certification information is available and clear to crews and operators is imperative to ensure appropriate decision making in the field. The following recommendation is proposed to address that:

Recommendation 1: **Ensure that certified and uncertified materials, systems, and processes are clearly distinguished to flight crews and mission planners.** Rather than only requiring that certified materials be appropriately indicated with seals or lettering, uncertified materials must also clearly be noted as such. Additionally, when producing and approving materials for use by flight crews or air operators, OEMs and regulators should conduct analyses to not only to determine that the intended interpretation is appropriate, but also to identify potential unintended interpretations of the language or presentation that may generate flawed mental models in readers.

Table 1
Flight crew contributions.

Unsafe Control Actions:

- **FC-UCA-1:** Took off in an elevated helideck using an aircraft not certified for elevated helideck operations

Mental Model Flaws:

- **FC-MMF-1:** Potential belief that aircraft is certified for elevated helideck operations [FC-UCA-1]
- **FC-MMF-2:** Potential belief that the procedures presented in S92A RFM Part 2 would lead, in a worst case scenario, to "limited exposure" to the possibility of ditching (a safe forced landing), instead of a crash [FC-UCA-1]
- **FC-MMF-3:** Potential belief in lower rate of sudden inflight engine shutdown than true rate [FC-UCA-1]
- **FC-MMF-4:** Potential belief that procedures in S92A RFM Part 2 are also certified. [FC-UCA-1]

Contextual Factors:

- **FC-—CF-1:** Rate of engine shutdown published by Sikorsky is 0.6 per 100,000 flight hours, reality in Brazil is over 2x higher [FC-MMF-3, FC-UCA-1]
- **FC—CF-2:** Air operator / customer determines the mission and operational profile the flight crew will be following [FC-UCA-1]
- **FC-—CF-3:** According to FAA AC 29–2C, the RFM should list all the operations for which the aircraft is certified in the "operating limitations" section. The S92A RFM does not include this list, meaning the flight crew has to read the entire RFM Part 1 to realize that performance charts for elevated helideck operations are not included (which would indicate aircraft is not certified in that condition). Performance charts for elevated helideck operations are instead found in Part 2 of the RFM, which is uncertified. [FC-UCA-1]
- **FC-—CF-4:** S92A RFM Part 2 says that not following the instructions in that section can lead to unsafe operations, despite those instructions not being certified. [FC-UCA-1]
- **FC-—CF-5:** Only explicit statement that S92A is not certified for elevated helideck operations was in Note 13 in Revision 9 of the S92A's Type Certificate Data Sheet (TCDS), seven years after original type certification of the aircraft [FC-MMF-1, FC-UCA-1]

Table 2
Operator Management / Customer Contributions.

Unsafe Control Actions:

- **OM-UCA-1:** Determined operation of rotorcraft in an environment it was not certified for (elevated helideck)
- **OM-UCA-2:** Did not provide flight crew with FAA-approved training for elevated helideck operations
- **OM-UCA-3:** As part of flight crew training, did not inform crews that S92A RFM Part 2 is not certified and that the performance charts included in Part 2 do not imply aircraft is certified for those operations

Mental Model Flaws:

- **OM-MMF-1:** Potential belief that aircraft is certified for elevated helideck operations [OM-UCA-1]
- **OM-MMF-2:** Potential belief that the procedures presented in RFM Part 2 would lead in worst case scenario to a "limited exposure" for ditching instead of a crash [OM-UCA-1]
- **OM-MMF-3:** Potential belief that procedures in S92A RFM Part 2 are also certified. [OM-UCA-1, 3]

Contextual Factors:

- **OM-CF-1:** In request for exemptions, operator does not mention the fact that aircraft is not certified for elevated helideck operations [OM-MMF-1]
- **OM-CF-2:** No clear statement in S92A RFM that aircraft is not certified for elevated helideck operations [OM-UCA-1]
- **OM-CF-3:** Flight Standardization Board (FSB) report does not establish training requirements for flight crews operating in elevated helideck, because aircraft is not certified for that environment [OM-UCA-2]
- **OM-CF-4:** FAA exemptions do not establish either the specifications for training, for checking, or the amount of training hours necessary for flight crews operating in the environment for which the exemption is granted (elevated helideck), as would otherwise be specified in an FSB report [OM-UCA-2]
- **OM-CF-5:** S92A RFM Part 2 says that not following the instructions in that section can lead to unsafe operations, despite those instructions not being certified. [OM-UCA-1]
- **OM-CF-6:** It is not typically expected that an aircraft operator has knowledge of aircraft certification regulation [OM-UCA-1]
- **OM-CF-7:** According to FAA AC 29–2C, the RFM should list all the operations for which the aircraft is certified in the "operating limitations" section. The S92A RFM does not include this list, meaning the operator has to read the entire RFM Part 1 to realize that performance charts for elevated helideck operations are not included (which would indicate aircraft is not certified in that condition). Performance charts for elevated helideck operations are instead found in Part 2 of the RFM, which is uncertified. [FC-UCA-2]
- —**OM-CF-8:** Only explicit statement that S92A is not certified for elevated helideck operations was in Note 13 in Revision 9 of the S92A's Type Certificate Data Sheet (TCDS), seven years after original type certification of the aircraft [OM-MMF-1]

Table 3
Aircraft manufacturer contributions.

Unsafe Control Actions:

- **OEM-UCA-1:** Produced aircraft that is not certified for its predicted operational environment (offshore elevated helideck operations)
- **OEM-UCA-2:** S92A RFM Part 1, Section 1, (Operating Limitations) states that the aircraft is certified for Category A and Category B operations, but does not mention the different Category A profiles the helicopter has been certified to (see Figs. 5- 7), per the guidance of FAA AC 29–2C
- **OEM-UCA-3:** S92A RFM Part 2 includes procedures for elevated helideck operations, which are technically beyond the operating limitations of the aircraft and mentions that these procedures require approval from the state of the operator's Civil Aviation Authority, with no mention for the reasons why this approval is necessary (because the procedure is not certified by the FAA, and exceeds operating limitations from S92A RFM Part 1)
- **OEM-UCA-4:** S92A RFM Part 2 does not define what "limited exposure" means, nor does FAA regulation
- **OEM-UCA-5:** Reported inflight engine shutdown rate of 0.6 per 100,000 flight hours, while some countries with mature S92A offshore operations present higher (over 2x) rates

Mental Model Flaws:

- **OEM-MMF-1:** Potential belief that RFM Part 2's usage of "limited exposure" language is consistent with definitions of "limited exposure" per EASA and ICAO regulations [OEM-UCA-4]
- **OEM-MMF-2:** Belief that worldwide inflight shutdown rate is representative of rate in localized regions [OEM-UCA-5]

Contextual Factors:

- **OEM-CF-1:** Certifying aircraft for elevated helideck operations would have increased cost and delayed certification schedule for OEM [OEM-UCA-1, 2]
- **OEM-CF-2:** Main competitor of S92A, Airbus H225/EC225, is also not certified for elevated helideck operations [OEM-UCA-1, 2]
- **OEM-CF-3:** Including language indicating that procedures in S92A RFM Part 2 are not certified could lead countries to limit operation of S-92 [OEM-UCA-3]
- **OEM-CF-4:** "Limited exposure" language is used in EASA and ICAO regulations, but not FAA regulations [OEM-UCA-4]
- **OEM-CF-5:** No regulatory authority identified inconsistent use of "limited exposure" language and requested correction of RFM, (e.g., by issuing an airworthiness directive) [OEM-UCA-4]
- **OEM-CF-6:** No regulatory authority identified missing list of Category A profiles in S92A RFM Part 1 and requested correction [OEM-UCA-2]
- **OEM-CF-7:** Engine shutdown rate is produced worldwide and not by region or country (some regions or countries may experience higher rates than the global average) [OEM-UCA-5]

5.2. Flawed certification decision-making

In attempting to understand how the contextual factors around the S92A RFM described above came to be, the CAST analysis revealed unsafe decisions surrounding certification at the aircraft manufacturer and regulatory levels.

Not including the list of Category A profiles the helicopter has been certified for, and including uncertified procedures for elevated helideck operations that are not easily distinguishable from certified procedures can both be seen as unsafe control actions at the OEM level. At the same time, no regulatory authority identified the missing list of Category A profiles in the RFM Part 1 or the elevated helideck procedures in Part 2 and requested corrections, providing little indication to the OEM that changes needed to be made. This inaction could stem from a potential flawed belief that the RFM was clear enough in its indication of whether the aircraft was certified or not, or a belief that pilots or operators would regularly consult the aircraft's Type Certificate Data Sheet (TCDS) to become aware of its certification status.

The original decision not to certify the S92A for elevated helideck operations can also be seen as a contribution, and was likely made by the OEM in the context of financial and schedule pressures, competing priorities, and available resources. The S92A's main competitor, the Airbus H225/EC225, is also not certified for elevated helideck operations.

However, as of 2021, around 70% of all S92As delivered were listed as operating in the offshore market. ICAO's Annex 8 states that an aircraft's design should not have any features or characteristics that render it unsafe under its "anticipated operating conditions", which ICAO

Table 4
Regulatory body (FAA) contributions.

Unsafe Control Actions:

- **FAA-UCA-1:** Permitted a helicopter whose predicted operational environment would be offshore elevated helidecks to not be certified for elevated helideck operations (FAR 29.60)
- **FAA-UCA-2:** Only inserted a note describing that the aircraft is not certified for elevated helideck operations (Note 13 in S92A TCDS Rev 9) seven years after original type certification
- **FAA-UCA-3:** Did not issue airworthiness directive that would modify S92A RFM Part 1 to make clear the list of Category A profiles for which the helicopter is certified (that would not include elevated helideck operations), with the understanding that operators and flight crews may not be regularly consulting TCDS and not aware of Note 13 in S92A TCDS Rev 9
- **FAA-UCA-4:** Did not make clear to other civil aviation authorities the need to include the contents of S92A TCDS Rev 9 Note 13 (a modification that affects operational safety) in their respective TCDSs for S92A
- **FAA-UCA-5:** Permitted S92A RFM Part 2 (uncertified part) to present performance information that are beyond operating limitations without making this information clearly distinguishable from similar performance data that are within limits (not enforcing compliance with FAA AC 29–2C)
- **FAA-UCA-6:** Published exemptions that include language indicating that 9 s of exposure time would lead to an "unscheduled landing or ditching" rather than EASA's exposure time definition (a helideck-edge strike; penetration into the dead's man curve over the elevated helideck during takeoff/landings; or forced landing with obstacles on the surface)
- **FAA-UCA-7:** Did not make clear in exemptions that 'exposure time' of 9 s requires maximum engine inflight shutdown rate of 1 per 100,000 flight hours
- **FAA-UCA-8:** Requested inflight shutdown rate from individual operators instead of from manufacturer in a five-year window per region (e.g., Gulf of Mexico)
- **FAA-UCA-9:** FSB report (which is still part of type certification materials) does not establish training requirements for flight crews operating in elevated helideck
- **FAA-UCA-10:** FAA exemptions do not establish either the specifications for training, for checking, or the amount of training hours necessary for flight crews operating in the environment for which the exemption is granted (elevated helideck), as would otherwise be specified in an FSB report

Mental Model Flaws:

- **FAA-MMF-1:** Potential belief that S92 RFM was clear enough in its indication of whether the aircraft was certified or not for elevated helideck operations (air operators may later have indicated it was not clear) [FAA-UCA-2, 3, 4, 5]
- **FAA-MMF-2:** Belief that pilots or operators will regularly consult TCDS and become aware of lack of certification through Note 13 [FAA-UCA-3, 4, 5]

Contextual Factors:

- **FAA-CF-1:** Main competitor of S92A, Airbus H225/EC225, is also not certified for elevated helideck operations [FAA-UCA-1]
- **FAA-CF-2:** TCDS revisions/notes occur regularly and it is not expected that FAA explicitly communicates every change to other regulatory authorities [FAA-UCA-4]
- **FAA-CF-3:** Explicitly stating that elevated helideck procedures (located in S92A RFM Part 2) violate operating limitations listed in S92A RFM Part 1 could possibly preclude operation of the aircraft in some countries [FAA-UCA-5]
- **FAA-CF-4:** FAA adopted different terminology than ICAO Annex 6 Part 3 Performance Classes, which may lead FAA experts to be unfamiliar with 'exposure time' definitions used by ICAO and EASA [FAA-UCA-6, 7]
- **FAA-CF-5:** 'Exposure time' is not defined in FAA regulations [FAA-UCA-6, 7]
- **FAA-CF-6:** When IFSD reporting was first established in Europe in 1999, service difficulty report infrastructure did not have the capability to measure inflight shutdown rate by country/region [FAA-UCA-8]
- **FAA-CF-7:** S92A was not certified for elevated helideck operations so FSB report did not need to include elevated helideck training [FAA-UCA-9]
- **FAA-CF-8:** FSB report is produced during type certification process, and is produced by the FAA's certification team. Exemptions are produced after the type certification process, and are made by the FAA's operational team, who may not have the appropriate information to establish clear training specifications/requirements [FAA-UCA-10]
- **FAA-CF-9:** Regulators typically do not perform a dedicated evaluation of whether the predicted and typical operational environment matches the certification application. [FAA-UCA-1]

defines as *"conditions which are known from experience or which can be reasonably envisaged to occur during the operational life of the aircraft"* [11]. The decision by the FAA to allow the S92A to not be certified for elevated helideck operations when its anticipated operating conditions were in the offshore market can also be seen as a contribution to the loss.

The S92A obtained its original type certificate in December 2002, and the Type Certificate Data Sheet (TCDS) included a note stating that: *"the rotorcraft must be operated in accordance with the FAA approved Rotorcraft Flight Manual"* [35]. The misunderstanding among pilots worldwide on the certification status of the aircraft for elevated helideck operations is possibly what led the FAA, in November 2009, to insert Notes 13 and 14 in Revision 9 of the TCDS [36]. These notes stated:

> **Note 13.** The S-92A rotorcraft has not been certified for Category A vertical takeoffs and landings. The operating limitations for the S-92A while configured Category A currently prescribe a minimum 30 knot VTDP. This includes a minimum rejected takeoff distance and precludes operating from a confined area such as an elevated helideck or helipad. (our italics)

> **Note 14.** The S-92A has been certified for Category A with a maximum passenger seating configuration of 19 passenger seats and Category B with a maximum passenger seating configuration of 9 or less passenger seats (…).

Though Note 14 was later included in the Part 1 of the S92A RFM [7], Note 13 has never been inserted in other FAA regulation or approved documents, including the TCDS for the Sikorsky S76 [37], which has also not been certified for elevated heliport operations in Category A as per Part 29, §29.60. Note 13 has also not been replicated in other civil aviation authorities' TCDSs, such as those of ANAC [38] or EASA [39].

In fact, in 2011, Revision 16 of the FAA's S92A TCDS [40] edited Note 13 and removed the part stating that it *"(…) precludes operating from a confined area such as an elevated helideck or helipad"*, as they had begun issuing of exemptions to Part 91, that allowed air operators to perform offshore elevated helideck takeoff/landings with the S92A in the Gulf of Mexico [41]. In these exemptions, it is stated that *"The FAA recognizes that there may be instances in which a safe forced landing may not be possible due to environmental or other factors"*.

The unsafe control actions listed in Table 4 are significant, and without further analysis, it is not possible to state conclusively how and why those regulatory decisions were made. However, the systems-theoretic lens through which CAST examines these decisions reveals that they have unintended consequences at the operational level. The following two recommendations are proposed to address unsafe decision-making at the regulatory level:

Recommendation 2: **Utilize CAST within the regulatory authority itself to identify more detailed causal factors contributing to unsafe decision-making.** To further identify the explanations behind the unsafe control actions listed above, CAST could be applied by a team within the certification authority itself, to identify more specific gaps in responsibilities and communications between internal groups that led these decisions to be made. A detailed CAST that explores the interactions within the "regulatory authority" box of the control structure could lead to more specific recommendations and opportunities for improvement on the part of that authority

Recommendation 3: **Further incorporate systems-theoretic analyses during the process of making and assessing regulatory and certification decisions.** As shown by the unsafe control actions identified earlier, there is room for improvement in how regulatory authorities examine and predict the system-wide effects of their decisions.

One of the key tenets of systems theory is the idea of a hierarchy of elements in the system that interact through feedback and control. By treating the national airspace system as a complex engineered system and modeling it in terms of feedback control loops, regulatory authorities may have a better chance of identifying unintended consequences of regulatory decisions even if they occur multiple layers apart from them in the control structure. Another tool in the STAMP framework, System-Theoretic Process Analysis (STPA) [42], provides a step-by-step process for analyzing the potential undesired scenarios that can stem from a decision. Applying these during and after certification can help identify gaps that lead to unsafe decisions throughout the system.

5.3. Inconsistent language and coordination across different regulatory authorities

The language used in the S92A RFM and other materials, and the decisions that surround that language, highlight inconsistencies and weaknesses in coordination between regulatory authorities that can contribute to flawed mental models at several levels of the control structure.

The two vertical takeoff and landing procedures for elevated helideck that are provided in the S92A RFM Part 2 use the terms "Limited Exposure" and "No Exposure" [7]. In the "Limited Exposure" procedure, the helicopter is exposed for a limited time to a "forced landing" in the event of critical engine failure, while in the 'No Exposure' procedure, the helicopter has performance for continued flight or landing at all times. FAA regulation, particularly 14 CFR Part 1, which defines key terms, does not include definitions of 'exposure' and 'safe forced landing'. These definitions are included in ICAO [43] and EASA [14] regulations as:

> **Exposure.** Any part of a flight during which a system or engine failure leading to a forced landing is likely to result in a hazardous or catastrophic outcome.
>
> **Hazardous.** Failure which would result in serious or fatal injury to an occupant.
>
> **Catastrophic.** Failure which would result in multiple fatalities, or loss of rotorcraft.
>
> **Exposure time.** The period during which the performance of the helicopter with the critical engine inoperative in still air does not guarantee a safe forced landing or the safe continuation of the flight.
>
> **Safe forced landing.** Unavoidable landing or ditching with a reasonable expectancy of no injuries to persons in the aircraft or on the surface. (our italics)

Per ICAO and EASA's definitions, exposure of any kind means the helicopter is exposed to a *hazardous* or *catastrophic* event in case of engine failure. On the other hand, the RFM indicates a "safe forced landing" as the worst-case scenario in case of engine failure when following the "limited exposure" procedure, which does not accurately represent a potentially catastrophic crash into the water.

On the FAA side, the exemptions provided to S92A operators also only speak of the possibility for a "deck edge strike" and an "unscheduled landing or ditching" [41], not a catastrophic crash. At the same time, the exemptions propose several mitigations that are meant to ensure that the S92A achieves similar levels of safety to Category A operations even in the uncertified environment. These include:

a) Requiring that air operators' make S92A engine historical data available and accessible upon the FAA's request, in order to provide ongoing surveillance of engine reliability [41,44,45,46,47,48,49].
b) Requiring that air operators' comply with the 'Limited Exposure' procedures listed in the S92A RFM, Part 2, Section III, Elevated Helideck Takeoff and Landing [41,44,45,47,48,49].
c) Requiring that air operators' computations of approach and departure profiles from elevated helidecks not exceed 9 s of "exposure", as required for ICAO Performance Class 2 with limited exposure [41,44,45,47].
d) Requiring that air operators' computations of the approach and departure profiles comply with EASA's 'Performance Class 2 with defined limited exposure (PC2-DLE)' procedures, with total maximum theoretical exposure times of 9 s or less, considering the planned takeoff or landing weight, altitude, temperature and wind [46].

However, these mitigations once again represent a misunderstanding of the meaning of "exposure" and of how "exposure times" are computed. ICAO and EASA set a threshold of acceptable catastrophic risk of 5×10^{-8} per takeoff/landing for elevated helideck operations, or one catastrophic event every 20 million takeoffs or landings. This allows for there to be 9 s in each flight during which a critical engine failure is allowed to lead to a catastrophic event, assuming a maximum rate of inflight engine shutdown of 1 per 100,000 flight hours. The FAA's proposed mitigations discussed in the exemptions imply that it is the "limited exposure" procedure that guarantees only 9 s of exposure to a catastrophic accident, when in reality it is the assumption around the rate of inflight shutdown that drives this number. This topic is further discussed in Section 5.5.

The reference to PC2-DLE as an acceptable EASA performance class also represents a misunderstanding of the concept, as PC2-DLE does not figure in the Joint Aviation Authorities' (JAA) original regulation, nor in EASA's current AirOps [14] regulations. PC2-DLE was in fact first presented to the aviation industry by the OEM Eurocopter (now Airbus Helicopters) in 2010, but does not appear in any regulation.

Addressing the inconsistencies across different regulatory authorities' materials and documentation requires strong communication and coordination channels, as well as standardized usage of technical terminology. The following recommendation is proposed to address this:

Recommendation 4: **Further standardize communication and improve coordination across regulatory agencies when dealing with regulation that differs across different airspace systems.** Though it is unreasonable to expect that civil aviation authorities across every nation converge on every decision, stronger coordination is needed to ensure that safety-critical regulatory information is shared in a clear and timely manner. Terminology should be standardized to ensure that regulatory materials developed in one airspace system are intelligible to operators in a different system. Operators, OEMs, and regulatory authorities themselves should be required to utilize terminology that is appropriately defined in that regulatory environment, or make clear reference to regulatory materials from other countries that contain appropriate definitions.

Communication is not perfectly continuous at all times, but is often triggered by different conditions. A list of criteria should be established that would trigger communication between regulatory authorities on safety-critical matters. Those criteria may be a fixed schedule of communication, may depend on incidents that happen and reports that are filed, or may be structured around completion of specific certification processes. For instance, the inclusion or removal of information about an aircraft's certification in OEM or regulator documentation (as was the case with Note 13 in the S92A RFM) could be a required trigger for communication across regulatory authorities. Establishing specific communication requirements ensures controllers have the appropriate feedback to know when their own controls need to be amended based on changes others have made.

5.4. Weak controls on training requirements

The complex interactions between certification and operation regulations for the S92A also create a gap in the training requirements for elevated helideck operations that becomes evident when analyzing these

interactions through CAST.

The S92A has a MTOW greater than 12,500lbs, so its pilots need a type certificate whose training requirements come from an FSB, as described in Section 2.1.1. Appendix 1 of the S92A's FSB Report [50] presents the flight training maneuver tables, establishing a necessary takeoff training event of "Category A with powerplant failure before Critical Decision Point – CDP" and a necessary landing training event of "Category A with powerplant failure after Landing Decision Point – LDP". However, the FSB report does not indicate which Category A profile (clear area, ground helipad or elevated helipad) this training applies to.

As a result, there is no requirement in the S92A FSB Report [50] that offshore air operators flying in USA receive training in Category A elevated helideck takeoff/landing with powerplant failure before/after CDP/LDP in flight simulators. The FAA approved training program provided by Sikorsky's official training provider (Flight Safety International) [51,52] includes powerplant failure training solely for Category A clear area (i.e., horizontal profile) operations. Regarding elevated helipad trainings, there are predictions for trainings in normal operation conditions only (i.e., without powerplant failure).

Additionally, in their exemptions to air operators, the FAA often requires that air operators' training programs include provisions for appropriate crew training on the profiles associated with 'Performance Class 2 with limited exposure' and 'PC2-DLE'. However, since the FSB report does not include those same training requirements, and the training provider's program does not either, operators are left with little guidance as to how that training should be conducted. At the same time, the FAA team that establishes the exemptions also has no feedback or guidance on how to determine training requirements for the elevated helideck operations they are allowing, as that is a responsibility typically assigned to the certification team.

In the language of CAST, poor feedback to the FAA's team establishing exemptions leads to a weak control regarding training requirements, that can ultimately result in operator training programs that are not sufficient to educate crews on how to deal with an event with potentially catastrophic consequences.

Recommendation 5: **Establish a system by which teams providing operational exemptions to certification regulations can develop and release detailed training requirements appropriate to those exemptions.** The responsibility to develop training requirements for operations permitted through exemptions should not fall upon the air operator, but should be assigned to a division within the FAA that possesses the appropriate information to do so. This division must be cognizant of the existing training requirements established by the FSB during the type certification process, as well as the reasons behind the need for a regulatory exemption.

5.5. Flawed assumptions around quantitative risk assessment

Finally, missing feedback on the metrics used to conduct risk analyses was also found to be a contributing factor to unsafe decisions at the operational and regulatory levels. ICAO and EASA set a threshold of acceptable catastrophic risk of 5×10^{-8} per takeoff/landing, or one catastrophic event every 20 million takeoffs or landings. As described earlier, this allows for there to be 9 s in each flight during which a critical engine failure would lead to a catastrophic event, though this crucially assumes a maximum rate of in-flight engine shutdown of 1 per 100,000 flight hours.

Though the published inflight shutdown rate from Sikorsky is 0.6 per 100,000 flight hours, some countries with mature S92A offshore operations present rates that are over twice as high as the worldwide published rates [8,33,53]. Though the reasons for this discrepancy have not been identified, probabilistic metrics of risk are highly dependent upon the validity of the numbers used, and it is important to recognize the assumptions baked into these numbers when making decisions based on quantitative risk. When regulators and operators do not have the appropriate feedback that assumptions used in risk assessments may no longer hold or may not hold in certain environments, they may develop a false confidence that their organization or system's safety performance is effective, when it may in fact be close to an accident [54]. Appropriate investigation of the reasons behind discrepancies in predicted and actual failure rates can help highlight assumptions used during certification or development that have since been invalidated.

Recommendation 6: **Reevaluate the use of lagging indicators and probabilistic risk in regulatory decision-making.** Reliance on indicators based on historical data requires careful consideration of the assumptions that underlie those metrics. As Leveson [55] argues, it can become increasingly difficult to quantitatively predict future risk when systems and environments change over time. Regulatory authorities should further explore the use of assumptions-based leading indicators [56] to understand whether the validity of a long-held assumption is still unbroken.

Recommendation 7: **Require that quantitative metrics claimed in an aircraft's certification basis be periodically audited in the future, compared to the original estimates, and flagged if it differs significantly.** Enforcing appropriate controls always requires appropriate feedback. If credit is claimed for quantitative failure rates or other metrics during any step of the certification process, these metrics must be continuously verified and analyzed for mismatches. When a mismatch is identified, the discrepancy needs to be flagged to all groups whose decision-making is based on that metric, including the groups establishing operational procedures, such that the aircraft's certification basis can be appropriately revisited.

5.6. Specific implications for the S92A

Though the CAST results and systemic factors discussed above highlight safety concerns that need to be addressed, they do not make S92A offshore operations inherently unsafe. The argument made in some of the S92A exemption requests to the FAA is that not granting the exemption would make the S92A "economically unfeasible" and could "result in their removal from service" [46].

The severe payload reductions claimed by operators, however, do not appear to be entirely true. Table 5, derived from information in the S92A RFM Part 2, presents the maximum payload capacity in number of passengers when taking off or landing from elevated helidecks using the "No Exposure" procedure in Part 2 [7]. Examining the payload capacity at different distances from the coast and different air temperatures reveals that operations can be performed with *zero payload reduction* up to 190NM from the coast, while still providing 15 ft of clearance from the helideck edge in case of a critical engine failure and 0 ft of clearance from sea (resulting in a true ditching rather than a crash).

6. Conclusions

The paper presented a systemic-theoretic assessment of a gap between the certification and operation of Transport Category rotorcraft, with specific focus on the Sikorsky S92A. A relatively new accident analysis methodology called CAST was applied to a hypothetical accident involving the S92A, closely related to a real incident reported to the FAA in a service difficulty report. The analysis revealed the flawed mental models on the part of flight crews and operators around the certification status of the S92A, stemming from unintended consequences of decisions made by the OEM and regulatory authorities. This study has also served as an example application of CAST to a primarily regulatory problem, demonstrating a unique use case for the technique. The framework of directly tracing unsafe control actions to mental model flaws and contextual factors, especially across different levels of the control structure, was found to be particularly helpful for analyzing accidents with complex human decision-making, and could be incorporated in guidance for performing CAST in the future.

Although CAST is a recognized investigation and analysis technique

Table 5
Sikorsky S92A maximum payload capacity in number of passengers and (in pounds) over offshore helidecks takeoff/landings without refueling available.

Helideck at 130NM from coast	Air Temperature (°C)		
	25	29	33
9 s exposure time	19 (6064)	19 (6094)	19 (5883)
15 ft helideck edge and 0 ft from sea clearance	19 (4964)	19 (4364)	19 (3964)
15 ft helideck edge and 35 ft from sea clearance	19 (3376)	18 (3158)	15 (2567)
Helideck at 160NM from coast	**Air Temperature (°C)**		
	25	**29**	**33**
9 s exposure time	19 (5778)	19 (5778)	19 (5598)
15 ft helideck edge and 0 ft from sea clearance	19 (4679)	19 (4079)	19 (3679)
15 ft helideck edge and 35 ft from sea clearance	18 (3091)	16 (2873)	13 (2281)
Helideck at 190NM from coast	**Air Temperature (°C)**		
	25	**29**	**33**
9 s exposure time	19 (5493)	19 (5493)	19 (5313)
15 ft helideck edge and 0 ft from sea clearance	19 (4394)	19 (3794)	19 (3393)
15 ft helideck edge and 35 ft from sea clearance	16 (2806)	15 (2588)	11 (1997)

Information based in S92A rotorcrafts' flight manual (RFM Part 2, Section III);
Considering S92A empty weight as per FAA Part 110: 18,000 pounds;
Most restrictive pilot weight as per FAA Part 110: 180 pounds;
Most restrictive passenger weight as per FAA Part 29: 170 pounds;
S92A fuel consumption at 4,000 ft cruise (IAS 135kt, TAS 142kt): 1350 pounds/h;
Fuel reserve for VFR flight at normal cruise fuel consumption: 20 min;
Helideck height overwater: 95 ft; and wind calm.

in the aviation industry, there are some limitations of our work that should be recognized. First, this work uses a hypothetical accident strongly based on a real incident. Details of the real incident were omitted in the SDR it was originally documented in, so the authors cannot conclusively state that the causal factors identified in CAST were true contributors to the documented incident. Ideally, an accident investigation should have access to all parties involved to conduct interviews and collect factual records. In this hypothetical case, some information was reconstructed from knowledgeable experts who could not comment directly about the real incident but provided information about common gaps and deficiencies that could explain similar behaviors. Additionally, the CAST analysis that was performed focused on certification-related issues, and it is therefore incomplete. A full CAST analysis would examine factors such as policy, Safety Management Systems (SMS), and standards development to understand why these gaps were overlooked at the time. Because the scope of CAST includes a wide range of causal factors, a limitation of the method is identifying when the analysis is complete and the relevant causal factors have been identified. This study cut off the analysis at the national regulatory level for conciseness, but there is limited guidance on determining when a sufficient analysis has been conducted.

It is important to note that the findings of this study do not make S92A offshore operations inherently unsafe, nor are they meant to attribute blame to any operator, OEM, or regulatory authority for any potential safety concern. Focusing on blame impedes learning from accidents by automatically assigning their cause as a failure on the part of an individual or organization. The intention of this study was instead to uncover how asymmetries of information among different elements of a system can have unintended and unsafe outcomes, and to generate recommendations that rectify these asymmetries.

The findings presented in this case study are also not complete, and further work can be done to better understand the interactions among other players in the offshore market and in the international aviation community. The findings here are also not unique to the S92A, but represent trends throughout the aviation industry. It is the hope of the authors that future efforts to address regulatory gaps will explore the potential of systems-theoretic approaches to address these gaps more broadly.

CRediT authorship contribution statement

Clementino R. Veras Neto: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Rodrigo L. Rose:** Writing – review & editing. **John Thomas:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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