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A systemic analysis of patterns of organizational breakdowns in accidents: A case from Helicopter Emergency Medical Service (HEMS) operations

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ABSTRACT

In recent years, many accident models and techniques have shifted their focus from shortfalls in the actions of practitioners to systemic causes in the organization. Accident investigation techniques (e.g., STAMP) have been developed that looked into the flaws of control processes in the organization. Organizational models have looked into general patterns of breakdown related to structural vulnerabilities and gradual degradation of performance. Although some degree of cross-fertilization has been developed between these two trends, safety analysts are left on their own to integrate this gap between control flaws and patterns of organizational breakdown in accident investigation. This article attempts to elaborate the control dynamics of the *Systems Theoretic Accident Model and Process* (STAMP) technique on the basis of a theoretical model of organizational viability (i.e., the *Viable Systems Model*). The joint STAMP–VSM framework is applied to an accident from a Helicopter Emergency Medical Service (HEMS) organization to help analysts progress from the analysis of control flaws to the underlying patterns of breakdown. The joint framework may help analysts to rethink the safety organization, model new information loops and constraints, look at the adaptation and steering functions of the organization and finally, develop high leverage interventions.

1. Introduction

1.1. Background and objectives

The occasionally but highly consequential failures that have occurred in safety-critical organizations have led to a substantial line of research on how catastrophic failures take place in socio-technical systems and how organizational vulnerabilities are implicated in such failures. Modern accident techniques have shifted their focus from shortfalls in the actions of sharp-end practitioners to the shortfalls in the capacities of organizations to bring about a safe system. In particular, Rasmussen [1] presented a series of models, including the AcciMap technique, that guide analysts to look beyond the immediate events involving individual operators and examine management factors that created the pre-conditions for accidents. Similarly, Leveson [2] developed the *Systems Theoretic Accident Model and Process* (STAMP) technique that focuses on the control processes and constraints between different levels in the safety management system. Systemic accident models have been particularly useful in helping analysts probe into the complicated interactions between system components that may lead to performance decrements and unfortunate events.

At the same time, other researchers have relied on organizational models to reveal organizational vulnerabilities and degradation phenomena that generate flaws in the control processes or the enforcement of constraints (see synoptic review in [3]). Perrow's 'normal accidents' model [4], for instance, has been extensively used to look into aspects of interactive complexity and tight coupling in the structure of organizations that make accidents virtually inevitable. Beer's Viable System Model [5] has been applied in accident investigation [6,7] to reveal problems in the way that organizations structure their operations and manage their 'requisite variety' to respond to adverse events in the environment. The literature that deals with degradation has arisen with the observation that it takes time before vulnerabilities escape the capabilities of organizations to deal with them. Turner's model of 'incubation' [8] has pointed to the gradual progression towards a failure that is not seen and the discounting of signals of an incipient disaster. This degradation has also been linked to the gradual built-up of latent failures and organizational omissions [9,10], the erosion of protective forms of slack [11], the drift of local practices from the overall plan [1] and the reinforcing loops [12] that move such practices further from the normative forms. These patterns of breakdown deserve further

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attention since they tend to repeat themselves in many industries, underlying the shortfalls in the actions of practitioners.

These two trends in the development of organizational models and techniques for accident investigation have been taken place in parallel, with some degree of cross-fertilization. Although both AcciMap and STAMP techniques take a systems perspective, they remain rather neutral with regard to specific models of organizational structures and processes. This increases the gap between organizational models and techniques of investigation, hence leaving practitioners and analysts on their own to integrate the vast literature of organizational breakdowns and apply it to their specific domain. The purpose of this article is to elaborate the control dynamics of STAMP on the basis of a theoretical model of organizational viability. In particular, the Viable System Model (VSM) seems to suit this objective as it has already been applied in several cases of accident analysis [6,7,13,14]. The Viable System Model (VSM, [15]) has been adapted to a certain degree to fit the progression from control flaws (in STAMP) to patterns of breakdown especially at the organizational and regulatory levels. To illustrate this link between STAMP and VSM, a case study was used from Helicopter Emergency Medical Services (HEMS).

This article is structured as follows. The remainder of Section 1 looks at the context of work of HEMS operations worldwide and presents three accidents that occurred in Greece. Section 2 presents a theoretical framework that integrates the STAMP analysis with the Viable System Model so that new categories of analysis are introduced. To illustrate the advances of the proposed framework, the STAMP technique is applied to the analysis of control flaws of the first HEMS accident in Section 3. Subsequently, the Viable System Model is applied (Section 4) to reveal the organizational breakdowns underlying the flaws of control algorithms identified with STAMP. Section 5 concludes this article with a discussion on the proposed framework.

1.2. The context of HEMS operations worldwide

Helicopter Emergency Medical Service (HEMS) organizations undertake a wide variety of operations throughout the world. A fleet of suitably equipped helicopters is dispersed strategically in the areas of interest, taking into account equipment and hospital availability. An Operational Control Center (OCC) is established in the capital city and is complemented with a number of command posts at carefully chosen ‘forward bases’. The OCC provides flight dispatches, supports crews in conducting flight assignments and coordinates with Air Traffic Control (ATC) for the safe and expeditious transfer of patients to the final destination. Helicopter crews, ATC controllers and OCC dispatchers are tasked with complex decisions such as sizing-up an escalating situation, utilizing information from multiple sources and balancing goal conflicts [15]. Time parameters are quite strict. Information uncertainty may trigger replanning of a flight while unforeseen delays may trigger route changes and rule adjustments in conducting the flight. For example, a Visual Flight Rules (VFR) flight expected to terminate before the sunset may be changed into a night VFR or an Instrument Flight Rules (IFR) flight in the darkness, which increases operational demands. Weather conditions may be deteriorating faster than expected, hence giving rise to trade-offs between direct routing through adverse weather and indirect routings around the danger area. Eventually the pressing need to use ill-equipped aerodromes, or even search for a suitable ground area for landing at night, usually adds to the complexity of operations. Flight crews, air traffic controllers and OCC personnel set the boundaries of an ad-hoc Joint Cognitive System, which is characterized by patterns of resilience, coordination and affordances [16].

The growth of HEMS industry was significant over the last two decades. Although it was perceived as safe sector of aviation, the number of HEMS accidents has alarmingly increased over the last years. In the US, a number of 85 HEMS accidents resulted in 77 fatalities in the period from 2003 to 2008. Inevitably, HEMS operations were brought into the attention of U.S. Government, the National Transportation Safety Board [17], the Federal Aviation Administration (FAA) and the aviation industry. FAA conducted a thorough analysis of HEMS accidents and identified three primary safety concerns: inadvertent encounters of Instrument Meteorological Conditions (IMC), night-time VFR flights and Controlled Flight Into Terrain (CFIT) cases. Similarly in Europe, HEMS operations were identified as the riskiest sector of aviation with a poor safety trend, which is complicated by a recognized inability to obtain valuable data and classify accurately their causes [18].

1.3. A description of HEMS accidents

Following aviation deregulation (summer of 2000), HEMS operations were nominated to HELITALIA, an Italian company that would conduct emergency medical services operations in the Aegean islands of Greece. Primary oversight of HEMS flights was formally assigned to ENAC, the Italian Civil Aviation Authority, with the Hellenic Civil Aviation Authority (HCAA) assuming an additional layer of control. After only six months of operations, the first accident occurred on January 14th 2001, in adverse weather conditions resulting in 5 fatalities. The flight departed from Athens to the island of Patmos in relative good conditions and a meteorological forecast of rapidly deteriorating weather from the west. During the return flight, the helicopter entered a storm cell near Athens aerodrome. Although it was night and the weather was bad (calling for Instrument Meteorological Conditions), the helicopter adopted a VFR flight. It crashed into the sea, a few miles away from Athens aerodrome. The continuation of the VFR flight into IMC conditions and the failure of the crew to recognize the adverse weather were cited as the most important causes of the crash [19].

The second accident occurred 15 months later (June 16th, 2002) with 5 fatalities. The helicopter crashed into a mountain during its initial climb phase, after departing from a heliport in Anafi, a small island near Santorini. Once again, the helicopter was flying VFR at night. The decision of the crew to take a shortcut by flying over mountainous terrain – rather than using the published departure procedure – was identified as the most critical of cause of the second incident [20]. Eight months later (February 11th, 2003) a third accident occurred in the vicinity of Ikaria aerodrome where a helicopter crashed into the sea while flying VFR at night during the final stages of the approach for landing [21]. Although the evidence was inconclusive, the investigation committee claimed that the cause of this incident was a major electrical failure encountered suddenly at the final stages of the approach, which was not diagnosed correctly. A few days later, the HEMS company ceased its operations under nationwide criticism for misconduct of operations.

All three investigations were conducted by an independent accident investigation board, using the guiding principles of ICAO. However, all investigations were severely affected by the absence of data from Cockpit Voice Recorders (CVRs) and Flight Data Recorders (FDRs) since no regulatory requirements existed worldwide for having such systems in helicopters. This very fact prolonged the investigations and led to many assumptions about the real causes of the accidents, relying only on ATC information (voice transcripts between ATC and the flight crew and also ATC radar data) since the electronic footprint of the three flights was minimal. Apparently, the investigation reports failed to provide any preventive function. On the contrary, they were used for legal cases against the organizations involved. Furthermore, many safety recommendations addressing HEMS operations (e.g., improve ATC communications with crews flying at low altitudes) have not being met until years later.

Our analysis of the HEMS accidents has been based mainly on the official reports and, to a limited extent, on informal discussions held with personnel from the Hellenic Civil Aviation Authority. The results reported in this article do not represent any 'objective' form of truth about the accidents but shed some light into the organizational context surrounding the accidents. In this sense, our discussions with practitioners from the field provided valuable information about general work habits and communication practices that prevailed in both the older and newer HEMS organizations. This information has helped us to take a deeper look into the organizational patterns that affected the HEMS operations and provided a useful basis for developing a joint STAMP–VSM framework for accident investigation.

2. A control theoretic approach to system safety

Systems thinking perceives of organizations as hierarchical structures with communication and control processes that operate at the interfaces between organizational levels and entail an upper level imposing constraints upon a lower one. Leveson [2] specified several control processes and constraints that affect safety management, using the STAMP technique. From the perspective of organizational cybernetics, several researchers [6,7,13,14] have adapted the functions of the Viable System Model to take into account the particular needs of safety organization. In general, there is a good agreement between STAMP and VSM about the systemic processes in managing safety as they are briefly described below.

Organizations that operate complex systems have to make tradeoffs between conflicting goals such as safety, production, delivery times and utilization of capacity [22]. This brings into the fore the role of organizational models that constitute the deepest set of beliefs about how the world works, about potential hazards and about perceptions of organizational capabilities. Safety goals are passed onto the supervisory level and are transformed into specific plans for action that are assigned to different personnel. Plans of action are not the only constraints imposed by the higher levels of control; other constraints may refer to availability of job means, resources and degrees of freedom allowed to operators. At the shop-floor level, operational practices adapt the safety plans to variations in the environment, making use of available resources and safety barriers. To assess the adequacy of safety plans, a feedback loop is established to the higher management levels. Although STAMP takes a systems control approach, it remains neutral with regard to specific human and organizational models. In order to look deeper into the causal mechanisms of control loops, this study has tried to link STAMP to a cybernetics model of organizations (i.e., the Viable System Model).

2.1. A viable safety management system

A viable model views organizations as a nested group of autonomous units that could be perceived as viable sub-systems in their own right. System 1 is the basic unit that comprises both a management and an operational element and interacts with the local environment. Systems 2–5 facilitate the work of basic units S1 and ensure a continuous adaptation of the organization as a whole. The five safety-related functions are as follows (see Fig. 1; Table 1): formulation of the safety-policy, safety-development,

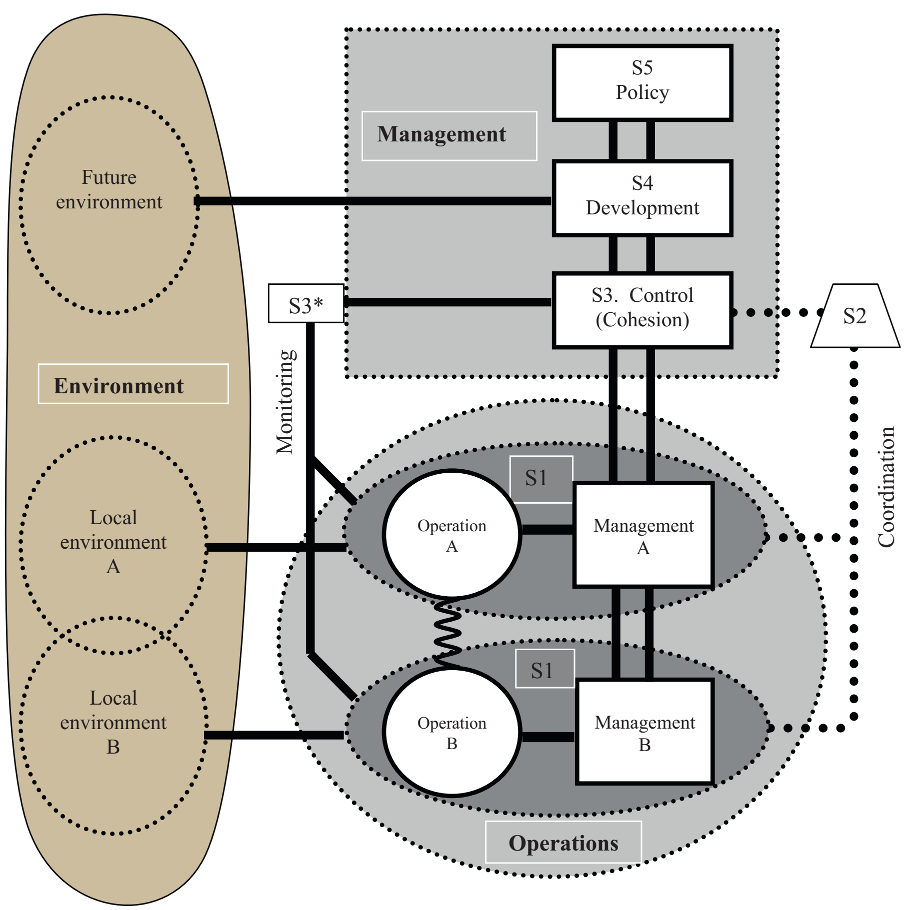


Fig. 1. A recursive template for the analysis of interactions between management, operations and environment.

Table 1
Description of the five safety functions of the Viable System Model (adapted from [6]).

System 1: safety policy implementation	System 1 is where the operational processes of an organization take place and therefore, it is where the interactions with the environment and the risks are created. From a safety perspective, system 1 implements the safety policies in the organization's operations. It consists of a management and an operational unit as well as its local environment; in a way, it is, on its own, a viable system that exists within the other four VSM systems. System 1 also relates to how sub-systems are grouped to form an organizational structure. In the case study, S1 is functionally decomposed into a set of sub-systems.
System 2: safety co-ordination	The function of system 2 is to co-ordinate operations and implement the safety plans received from system 3. Conflicts arising amongst S1 units must be resolved so that a collaborative atmosphere is created in the organization. S2 has an 'anti-oscillatory' function to play in that it attempts to minimize fluctuations between S1 operations. This is achieved by the provision of coordinating facilities such as, direct supervision and mutual adjustment.
System 3: safety control loops	System 3 is concerned with the provision of cohesion and synergy to a set of S1 units. From a safety viewpoint, system 3 is responsible for maintaining risk within an acceptable range in S1 operations and for ensuring that S1 units implement the organization's safety policy. Safety plans and standards are received from S4 and S5 while information about safety performance is collected from S1 and S2 to close the feedback loop between planning and monitoring of safety. Therefore, S3 evaluates accountability of operations and allocates resources to S1 units to accomplish safety plans. S3 needs to ensure that the S1 reports reflect the current status of operations and that S1 are also aligned with the overall safety policy. For this reason, system 3 is employed to conduct audits sporadically into the operations of S1 units.
System 4: safety development and adaptation	System 4 plays an intelligent function as it scans the environment for threats and opportunities while looking inside for internal strengths and weakness. It conducts safety research and development (R&D) and suggests changes to the safety policies for the continual adaptation of the whole system to the changes of the environment. To ensure that safety plans are grounded in an accurate appreciation of the system, the intelligence function should contain an updated model of system capabilities. Finally, it deals with confidential or special information communicated by practitioners about near-misses and work problems to learn from actual practice. Santos-Reyes and Beard [6] have assigned this function of organizational learning to a system 4.
System 5: safety policy	System 5 plays the policy-formulation function, representing the current beliefs, norms and assumptions about the environment and the internal system capabilities. It also monitors the interaction of S3 and S4 to achieve a balance between exploitation of existing safety rules and exploration of new safety concepts. These policies should also promote a good 'safety culture' throughout the organization.

safety-functional, safety-co-ordination and safety-policy implementation. The VSM model is proposed as a sufficient structure for an effective safety management system.

The VSM perspective highlights the recursive structure of organizations. The concept of recursion is intended to clarify whether a safety management system refers to an entire organization, several parts of it, or just part of it. Recursion implies some sort of autonomy and 'self-regulation' at each level of description in the sense that the same five functions apply to each individual unit to ensure viability on its own. In a sense, system 1 can be seen as a group of sub-units that have relative autonomy in carrying out their tasks. At the same time, however, sub-units should comply to the requirements of the safety management system as a whole. Hence, VSM brings into the fore the balance that must exist between autonomy and centralization of control. This is a delicate balance as sub-units must not become isolated but, equally important, must not drift from the overall safety policy.

Two other important issues that VSM highlights regard the interactions between planning and monitoring as well as between strategy and organizational structure. First, it has been recognized that planning and monitoring are necessary processes for a management unit to control its operational element. However, the two processes are coupled and form a closed control loop, which often passes unnoticed and leads to several problems. For instance, the separation of decisions about performance-planning from decisions about resourcing can lead to arbitrary targets or cuts in resources. Hoverstadt [23] discusses the problem of 'reverse polarity' where measures of performance are used not to monitor a process but instead to drive the planning of the process. Similarly, there appears to be an interaction between strategy and structure that seems to go unnoticed in many safety improvement campaigns. Strategy should be built up throughout the organizational structure where the interests of individuals and teams at different levels are equally reflected in decision making. Failure to do so may result in a safety campaign that may not succeed to reach certain parts of the organization.

According to VSM, the structure of an organization can be described by the way that systems 1 and 2 have been designed. Structure reflects the organization of system 1 units into higher-order units (e.g., functional similarity versus autonomous grouping) as well as by the type of coordination that is achieved between units. On the other hand, strategy refers to the managerial functions of systems 3, 4 and 5 that determine how organizations control their processes and adapt to the environment. The Viable System Model highlights both aspects of interaction between strategy and structure.

Finally, the Viable System Model looks at the way that organizations adapt to the environment. System 4 plays an important function in scanning the environment for threats and opportunities so that new concepts of operation and safety are explored. It addresses the process of organizational learning and change by maintaining a balance between exploration and exploitation.

Several studies have employed these safety-related VSM functions to analyze the structure of the safety management system in organizations [6,7,13,14] producing similar results to STAMP analysis. The purpose of this article, however, has been to adapt the VSM functions so that analysts can look deeper into the organizational patterns of breakdown that lie behind flaws in the control processes and coordination of operational units. For this reason, a mapping is proposed between the STAMP categories of analysis and the VSM principles of organization.

2.2. Control flaws and underlying organizational breakdowns in accidents

Although basic events and action failures are the starting point, systems thinking focuses on the system structure and control mechanisms. According to *STAMP*, problems in the structure and control of complex systems arise mainly due to control flaws such as inadequate design or enforcement of constraints on the lower levels. For each control flaw, it will be necessary to evaluate the context in which decisions are made and the work influences at play in order to understand how and why unsafe decisions have been made. Table 2 shows a classification of control flaws, that is, the error modes or observable failures of control loops [2]. However a deeper analysis of causal

Table 2
Control flaws leading to accidents [2].

1. **Inadequate enforcement of constraints:**
   - 1.1. Unidentified hazards.
   - 1.2. Inappropriate, ineffective or missing control actions for identified hazards:
     - 1.2.1. Design of control algorithm (process) does not enforce constraints:
       - Flaws in creation process.
       - Process changes without appropriate change in control algorithm (asynchronous evolution).
       - Incorrect modification or adaptation.
     - 1.2.2. Process models inconsistent, incomplete, or incorrect:
       - Flaws in creation process.
       - Flaws in updating process (asynchronous evolution).
       - Time lags and measurement inaccuracies not accounted for.
     - 1.2.3. Inadequate coordination among controllers and decision makers (boundary and overlap areas).
2. **Inadequate execution of control action:**
   - 2.1. Communication flaw.
   - 2.2. Inadequate actuator operation.
   - 2.3. Time lag feedback.
3. **Inadequate or missing feedback:**
   - 3.1. Not provided in system design.
   - 3.2. Communication flaw.
   - 3.3. Time lag.
   - 3.4. Inadequate sensor operation (incorrect or no information provided).

Table 3
Description of the extended categories of analysis in STAMP.

Steering of control algorithms	Control algorithms are designed with a goal in mind that should be attained and sustained over time. Practitioners face many challenges in articulating hidden goals, balancing conflicts, and seeing long term consequences. In some cases, a goal may be judged as a poor choice but a careful investigation may reveal that this is a reconciliation of conflicts at work beyond the control of individuals. Hence, analysts should try and trace implicit goals at work that are not clearly articulated and tacit constraints from the organization. Steering plays a similar function to system 5 in balancing exploitation and exploration.
Adaptation to environmental demands	Organizations operate in an open environment and their exchanges can be rich and dense. Increasing competition, societal pressures and de-regulation inflict changes in technology, reforms of organizational structure and adaptations (e.g., updating of procedures). Organizations must adapt their structure and processes to manage these demands. Adaptation to environment and coordination between 'running' and 'changing' the system are functions related to system 4.
Modeling	All managerial and operator interventions are associated with a 'mental model' of what safety means to them. People construct their own 'theory' of potential hazards, accident causes, affiliations to receive support, and risk strategies. Their models are vehicles for understanding and directing attention to critical signs of risk. Mental models help managers and operators challenge their understanding and remain vigilant to the possibility of failure [29]. They are important for the intelligence function of system 4 to ensure adaptation.
Monitoring and auditing	Information handling difficulties may relate to the nature of the information itself (e.g., ambiguous data), the characteristics of the observer (e.g., not recognize its significance) or the environment (e.g., distractions). In studying disasters, it is important to pay attention to the distribution of information, to the structures and communication networks within which it is located, and to the nature of the boundaries which impede the flow of information. Organizations create assumptions about what is given value as information, how it can be communicated, and what can be ignored.
Planning of control algorithms	Control algorithms should be designed according to a safety plan that specifies the sequence of actions, the slack that exists, and the degrees of operator freedom. In this sense, a work practice is an algorithm with specific features such as, level of granularity, degree of freedom and temporal constraints (e.g., when practices evolve at a higher pace than the updating of procedures).
Coordination	Cooperation of multiple units raises many important issues with regard to the delineation of responsibilities, reconciliation of different views and decisions, and communication among team members. When there are multiple controllers, decisions may be inadequately coordinated, including communication errors, unexpected side-effects and conflicting control actions. When coordination crosses organizational boundaries, people may not be able to see how their actions affect others or may not be motivated to do so due to a 'silo' mentality.
Implementation of safety policies	Safety policies and plans are implemented at the sharp-end where practitioners interact with the internal system (e.g., displays, controls and procedures) and the environment (e.g., responding to weather conditions and changing air traffic). To cope with economic and temporal demands, practitioners often have to fall back on experience and rely on habits that seemed to worked in the past. The danger is that, as habitual actions gain strength by their everyday use, practitioners may not see certain countersigns or exceptions that make rules unsuitable to the current situation. In this sense, the balance of autonomy and control at systems 2 and 3 are likely to influence implementation of safety policies.

mechanisms of control loops could be made with reference to organizational models. Several system dynamic models have been used in the literature to expand the analysis into system archetypes that underlie flaws in control loops in system safety, organizational learning and safety reporting systems [24–26]. In order to provide a basis for integrating several *patterns of breakdown* that were assembled from a literature survey, this study has tried to link STAMP to the Viable System model (VSM).

The following changes have been proposed to the categories of STAMP. The category of control algorithms has been refined in terms of two aspects of steering and planning (see Table 3). Steering refers to the values and goals of different individuals across organizational sectors. Planning refers to temporal and spatial constraints of control algorithms (e.g., how a plan adapts to situational changes and how it is distributed across multiple actors). A second refinement has been made to the coordination category of STAMP to create an adapting function outside the organizational boundaries (see intelligence function in VSM) and a controlling function within the organization. At a meta-level, organizations need to adapt their collaborative work to changes in environmental demands (i.e., 'changing the system') whilst at the operational level, local coordination is needed to carry out complex tasks (i.e., 'running the system').

As a final point, the planning and monitoring functions in STAMP correspond to the control function of VSM that is required to achieve cohesion of operational units and ensure that local coordination does not drift from the overall plan. The extended categories of control in Table 3 can accommodate the organizational cybernetic perspective (VSM) and provide a better basis for integrating several patterns of breakdown presented in the literature [23,27,28].

3. STAMP analysis of control flaws

As mentioned, STAMP analysis focuses on the interactions between different levels in a socio-technical system. The STAMP model does not explicitly represent the sequence of events up to the accident so that analysts focus on organizational factors rather than the immediate events that are usually associated with operators at the front-end. However, a timeline of events (see Table 4) that complements the textual description of the first HEMS accident can be useful as a starting point.

Fig. 2 illustrates the results of applying STAMP to develop a control diagram of the wider organizational context of HEMS operations together with some safety requirements and constraints. Each controller in the control structure plays a role in enforcing some safety constraints to ensure viability of operations. ICAO is responsible for regulating and overseeing the safe operation of aviation systems by passing laws and providing policies to each country's regulatory authority. In turn, regional authorities (e.g., HCAA and ENAC) ensure that appropriate ATC facilities are established to safely and efficiently guide air traffic, maintain safety guidelines, establish budgets for operation and staffing levels and comply with ICAO regulations. These safety requirements and constraints set the operating environment for flight companies and their crews. In particular, flight companies (e.g., HELITALIA) have responsibility for the safe and timely transport of passengers, for ensuring crews have available all necessary information for each flight and for providing pilot training tailored to the peculiarities of the operating environment. Finally, crews have direct responsibility for flight safety. They operate the aircraft in accordance with company procedures, ATC clearances and ICAO regulations. Any problems endangering safety should be reported to the flight company and the regulatory authorities. After the analysis of the hierarchical organizational structure, the STAMP technique progresses by considering each of the control loops that are identified in the socio-technical system. Fig. 3 shows several inadequacies in the control algorithms and mental models of controllers as well as the work context in which these took place.

3.1. The crew performance

HEMS operations may be carried out in adverse conditions, which increases uncertainty and coordination demands. For instance, a VFR flight may be performed at night, in rapidly deteriorating weather, from a forward base to an ill-equipped heliport in a small island to collect a patient and then fly to the capital city with the necessary hot refueling (i.e., refueling with the crew and passengers on board in another small island). Crews flying over the Aegean sea, may encounter severe weather patterns, thunderstorms and gusting winds sweeping Greece from west to east. As they approach Athens, crews are more likely to face the dilemma to continue or abort mission a few nautical miles from their destination. This context of operations requires high experience at VFR flights at night-time in an unforgiving environment of flying between small islands. It also requires many preparations and extensive familiarization with the work practices of ATC controllers and weather debriefers since formal supervision of heliports at small islands is rather poor. These conditions that influenced the performance of flight crews have been captured in the STAMP analysis of the context of work for the HEMS crew and air traffic controllers (Fig. 3). The most critical causal factor was the continuation of VFR flight into IMC and the delay of the crew to abort mission and return to the alternative airport of Syros. Although the co-pilot had made all arrangements for keeping Syros airport open for a possible landing, he closed up this option prematurely. The flying crew had a lot of experience with rescue operations over mainland but little exposure to the adverse conditions encountered in small islands.

Table 4
Timeline of first HEMS accident.

Agents	OCC	ATC	Flight crew	Context of work
Athens aerodrome	A VFR flight plan is filed as a round trip Athens–Patmos	Receives, checks and accepts VFR flight plan	Captain orders OCC to send flight plan to ATC	Limited daytime for VFR flights as weather is deteriorating
Flying to Patmos over Mykonos	Senior flight officer leaves assistant in OCC	Informs crew that weather at Athens is below VFR minima	Helicopter stops at Mykonos to refuel which adds to delays	Air to ground communications unreliable at low altitudes
Returning to Athens	Junior assistant is alone at the center	Mykonos provides an outdated weather report	Requires that Syros airport remains open as a back-up plan	Weather is deteriorating rapidly at Athens
Entering Athens TMA (Terminal Control Area)		Approach control warns crew about severe weather	Continues flight under VFR conditions in thunderstorm	Night and IMC conditions prevail
Flying inside Athens TMA		Approach control is busy with other aircraft on holdings and negotiating diversions	Unable to continue VFR, requests vectors for ILS (Instrument Landing System) approach	Night, IMC and turbulence conditions
A few miles away from destination		Asks crew if they are able to hold over VOR of AIGINA	Accepts holding but later attempts to turn away from storm	Handling of helicopter becomes very difficult and leads to crash

Their mental model of rescue operations at sea was inadequate so the crew, possibly unaware of the impact of gusting winds, continued to fly into the thunderstorm.

3.2. Organization of the flight company

An established solution to achieving operational agility is to complement the helicopter fleet with turboprop or jet airplanes that connect the capital city with the 'forward bases'. In this case, helicopters operate locally by transferring patients from the nearby areas to the forward base while airplanes are used to carry patients to the capital city. This type of mixed helicopter and airplane operations maximizes the advantages of airplanes (e.g., increased cruise speed, ability to fly on top of active weather) and helicopters (e.g., ability to land nearly anywhere without the need of sophisticated ground-based equipment). It is evident that the operational flexibility of HEMS organizations should favor a mixed fleet of helicopters for local operations and light airplanes to connect with the capital city in combination with high operational expertise cultivated with rigorous training programs. However, the initial plan for a mixed fleet was degenerated into a helicopter-only fleet due to a failure to consider user requirements at the initial stage. This high-level decision crippled the agility needed for HEMS operations, especially in adverse weather conditions. In addition, HELITALIA established a less formal and inadequate supervision system on the grounds that the fleet did not have any aircraft elements. Organizational problems at the Operational Control Center (OCC) had not been brought into the light since the Memorandum of Understanding (MoU) between the two regulatory authorities (i.e., ENAC and HCAA) had not been signed yet.

As a result of the organizational problems and the belief that previous experience with land rescue operations over Italy could easily transfer into sea operations over the Aegean sea, HELITALIA failed to design and enforce many control processes. For instance, there was no direct line between OCC and meteorological office, the monitoring of flights was inadequate as the senior officer left the OCC, and the flight duties of the operations director interfered with his managerial duties at company level. These control flaws resulted in the flight crew receiving outdated weather information and inadequate monitoring from the senior flight officer with regard to flight continuation to final destination.

3.3. Communications with air traffic control

ATC communications were very busy during the return portion of HEMS flight as weather was deteriorating, many commercial

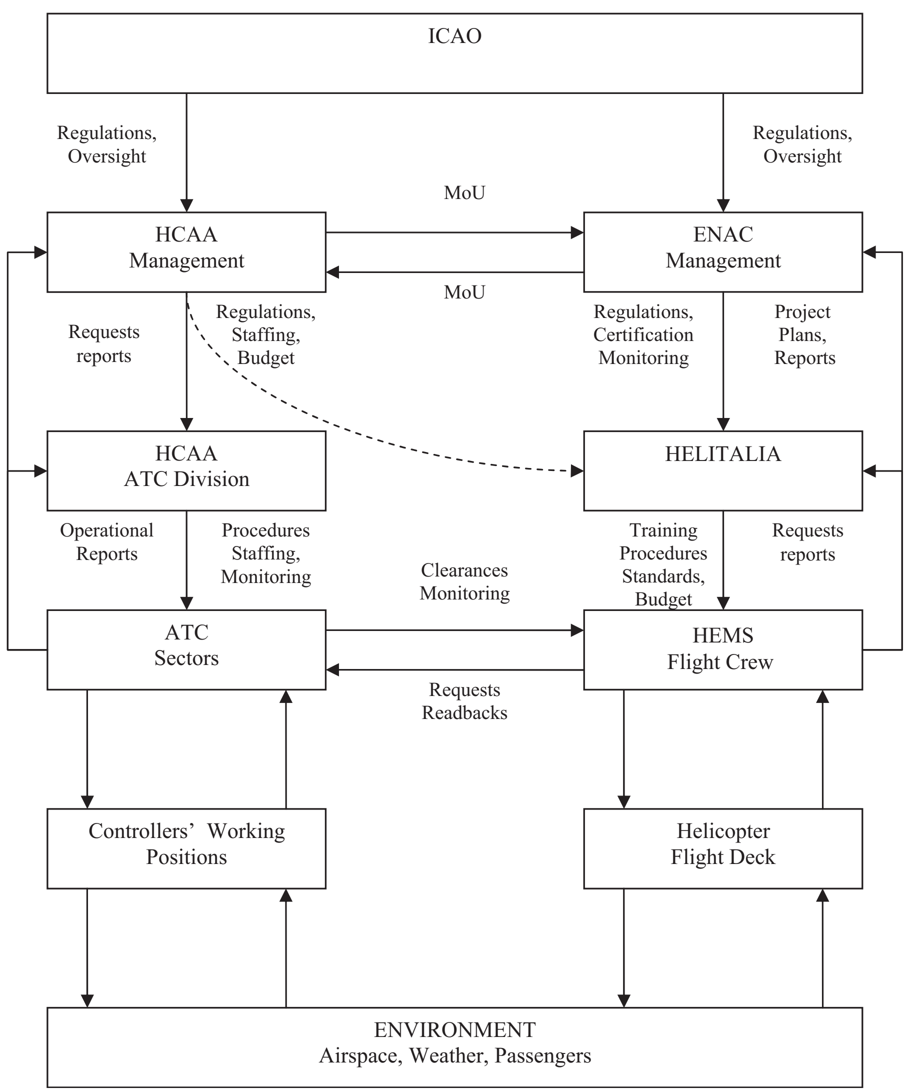


Fig. 2. A hierarchical representation of the wider organization of HEMS operations (STAMP perspective).

aircraft were in holding patterns above the destination airport (Athens) and some were running out of fuel. In addition, radio communications with the HEMS crew were impeded by the low altitude flight. This context of work may account for several omissions on the part of air traffic controllers that had an impact on the HEMS flight. First, the IFR controller did not update the transponder code for the HEMS flight, which caused the approach controller to lose valuable time in trying to identifying the HEMS flight. Second, the controller at Mykonos airport provided outdated weather information (that was better than the actual and did not warrant a change of the flight plan) and failed to caution the crew about the deteriorating weather. Third, ATC communications were overloaded with a high transfer of information that could not make sense by the HEMS crew. Finally, the approach controller was absorbed into communications with commercial flights on holding that were low on fuel and failed to give adequate attention and priority to the HEMS, which was a sanitary flight as required by regulations. These inadequacies in managing workload and communications have been used as markers of poor teamwork in safety critical domains [30].

3.4. Oversight by regulatory authorities

The Hellenic Civil Aviation Authority (HCAA) and its Italia counterpart ENAC were jointly responsible for overseeing the flight operation of HELITALIA. However, a patchy form of joint regulatory oversight was established between HCAA and ENAC, which complicated the oversight process. The Memorandum of Understanding (MoU) was signed in a hurry two months after the first accident and this delay gave rise to ambiguities in the role of each regulatory authority. In addition, it contributed to a compliant attitude of HELITALIA that failed to establish the formal organizational processes described earlier.

As it can be seen from Fig. 4, HCAA regulatory attention was diverted far from HEMS operations due to its pre-occupation with multiple urgent projects. First, HCAA was in the midst of a major

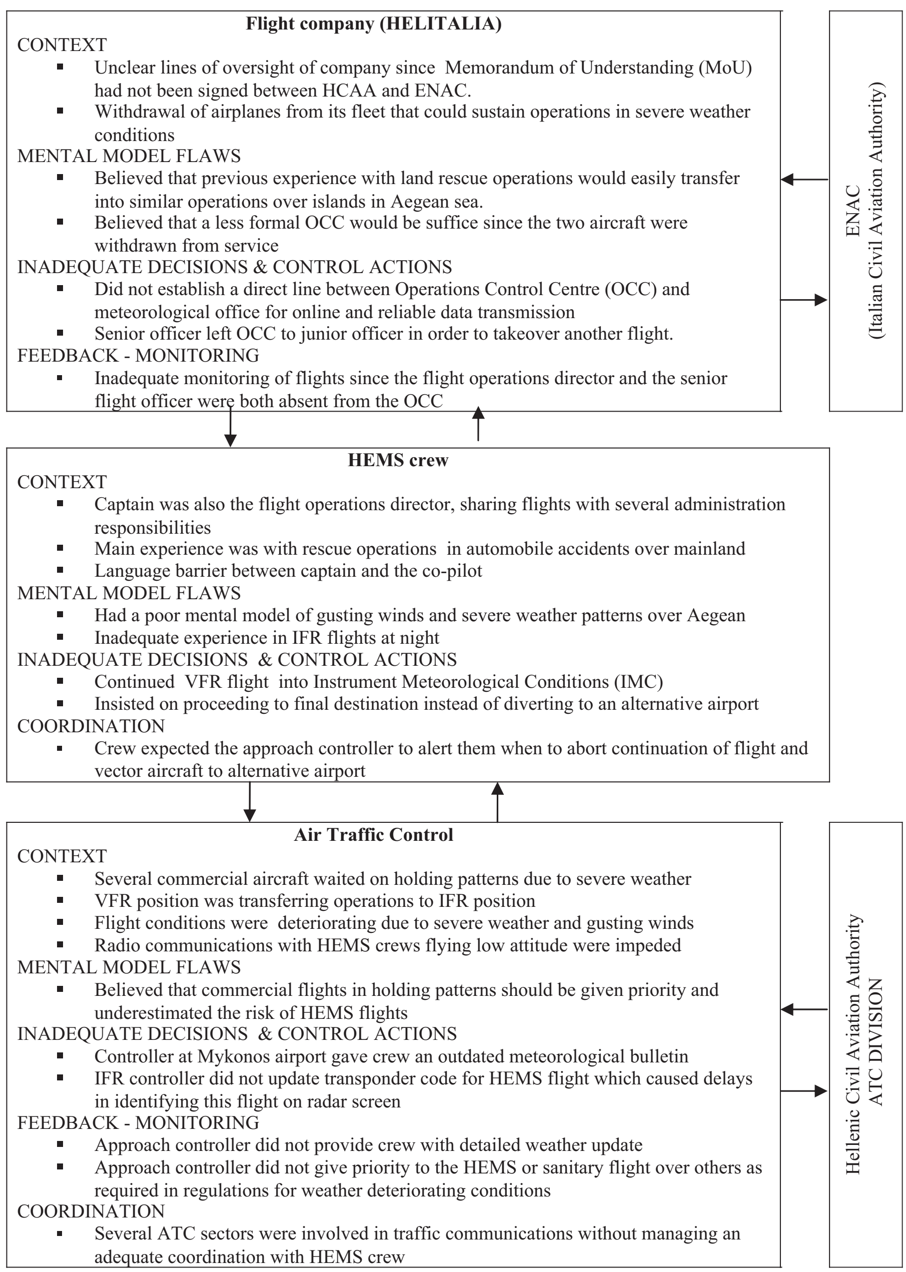


Fig. 3. Flaws in the control loops regulating the interactions between flight crews, air traffic control and flight company.

Regulatory authority (HCAA)

CONTEXT
- HCAA was in the midst of a major transition from procedural to radar services
- A relocation of the Athens aerodrome drained nearly most HCAA recourses.
- Other high profile projects were running in parallel for the Olympic games

MENTAL MODEL FLAWS
- Believed that new HEMS organization will be as successful as the previous one
- Poor perception of risks and problems involved in HEMS flights

INADEQUATE DECISIONS & CONTROL ACTIONS
- Did not prepare safety assessments of newly built heliports in Aegean islands
- Did not evaluate operations at the control centre of HELITALIA

COORDINATION
- HCAA did not coordinate with ENAC to sign Letter of Memorandum

Fig. 4. Control flaws at the regulatory level.

ATC transition from procedural to radar services due to another aviation accident. Second, a complicated and time-pressured relocation of Athens aerodrome (i.e., from Elliniko to Spata) was in progress, which drained nearly all available HCAA recourses. Third, safety assessments of the newly built heliports in Aegean islands were not prepared at the time and ATC supervision of flights was not adequate at small island heliports. In general, the risk associated with HEMS flights was not thoroughly evaluated and was considered to be rather low as regulatory attention was diverted to high profile projects. Furthermore, the earlier HEMS organization was very successful in the past as it relied on a mixed mode of civilian and military operations; hence, HCAA perceived no strong reason to divert resources from its urgent projects to the evaluation of the new HEMS organization. This compliant culture of HCAA may explain the delays in taking action even after the first HEMS accident. Neither ENAC however took an active role in overseeing HELITALIA operations despite the fact that ENAC was the primary regulator since the HEMS helicopters were registered in Italy. Poor overseeing of the flight company by HCAA and ENAC contributed to a low perception of risk of HEMS operations and an inadequately organized OCC.

In many respects, the application of the STAMP technique has helped us to identify areas of the incident that did not receive sustained attention within the official documentation. In general, it helped us probe into the interactions between different organizations and identify how critical tasks and roles were coordinated between various individuals in the cockpit, the air traffic control and the flight company. By relating the control actions of practitioners to the context of work and their mental models of the situation, analysts can zoom out of the chain of events into the causal factors of the wider environment. The STAMP control analysis extends from these interactions to consider the relationships of the course of events with the management of the flight company and the oversight process of regulatory authorities. Hence, poor monitoring of the flight company and omissions in oversight have reduced the capacity of the HEMS organization to respond to deteriorating flight conditions.

4. VSM analysis of organizational breakdowns

The VSM sets down the principles that create viability in organizations, which is the capacity to adapt appropriately to a chosen environment or change the environment to suit themselves. A key concept is how organizations handle the complexity of both their environment and of their own activities. VSM deals with this complexity in two ways: by looking at the balance of complexity between parts of the system (i.e, the law of requisite variety) and by unfolding in a recursive structure in which systems are made of sub-systems with the same generic characteristics. The recursive structure of organizations implies that the same systemic principles are replicated at each of the sub-systems that are revealed in the unfolding of complexity.

Fig. 5 shows a VSM representation where a basic structure is repeated throughout the organization, consisting of a management unit (rectangular boxes) and an operation activity (oval shape) that interact with a local environment. Management–operation units can be grouped together into higher order operations that have their own functional organization and coordination mechanisms (C). Coherence and control of operations is achieved through the processes of planning and feedback (PF). Two additional management functions are modeled in their interactions with operations, that is, modeling and steering (MS). Interaction with the environment is modeled as a process of physical and intellectual adaptation (A). For an operational unit, physical adaptation includes, monitoring and responding to changes in airspace and weather conditions. Intellectual adaptation for management units includes, scanning the environment for safety risks and complying with regulations. Adaptation can also be seen as a process of amplifying variety of one's own capabilities or attenuation of the variety or complexity of the environment. Finally, physical inter-dependencies between operations are modeled as zigzag lines in Fig. 5. All interaction and control processes have been selected in Table 3 so that they map onto both the VSM and the STAMP frameworks.

Interactions between the three elements (i.e., management, operations, environment) can also be modeled as a process of balancing complexity or variety between them. In organizational terms, balancing complexity ensures that the capabilities of a management unit should be sufficient to deal with the complexity of the operational problems, which they have to deal with. Variety relates to complexity and refers to the number of states that a system may be found, to the range and quality of means and skills utilized to cope with a problem, to the amount of information to be processed and so on [31]. In principle, the concept of variety can be used to compare the relative complexity of systems rather than to get an accurate measure of complexity; for example, how can an increase in the complexity of the environment be balanced by an increase in the variety of the organization. An analysis of the ways in which organizations manage to balance variety has important implications for their ability to manage safety. Fig. 6 shows how HEMS organizations can succeed or fail in managing safety by amplifying or attenuating variety in their own its capacity and the environment.

HEMS flights may encounter a range of critical conditions (e.g., adverse weather, gusting winds and ill-equipped heliports) that increase their complexity. An organization can attenuate the complexity of the environment by several means such as improving facilities at heliports, minimizing delays and providing accurate weather reports. On the other hand, certain factors may amplify or attenuate the variety of the organization to respond to critical situations. Therefore, it is worth looking into how the older and new HEMS organizations managed their own variety. In the past, HEMS operations in Greece were conducted by a combination of airplanes and helicopters of the Hellenic Army, Navy and Air Force in close cooperation with the national carrier Olympic Airways (OA). Military helicopters were utilized to fly patients from smaller to bigger islands and latter transfer them to Athens with civil or military airplanes. In extreme cases, navy warships were used to transfer patients from small islands in adverse weather conditions when flight conditions deteriorated drastically. In this sense, the older organization had a broader boundary than the new one since the military capabilities became part of its own variety of coping skills. Although not formally organized, this concept of operation was quite successful with a good safety record.

Its success could be traced into the following factors:

- There was a wide range of helicopters, airplanes and even warships available for HEMS operations.
- Civil and military flight crews were largely familiar with the terrain and unique weather patterns in Aegean sea.
- Olympic Airways (OA) was tasked with having an airplane on readiness at night in Athens to conduct HEMS flights to the islands.
- Certain OA connections with the islands accommodated several HEMS requests with a minimal disruption to their operations.
- All crews had a lot of domain-specific experience in adverse flight conditions at Aegean and were familiar with all other aviation sectors.

As a result, the older HEMS organization managed to respond to the complexity of the environment by amplifying its own variety of performance. In fact, 'balancing variety' is the first organizational principle according to which "managerial, operational and environmental varieties, diffusing through an institutional system, tend to equate; they should be designed to do so with minimum damage to people and to cost" [5]. These adaptation mechanisms, unfortunately, were not noticed by the new HEMS organization (i.e., HELITALIA) that relied only on a fleet of helicopters with pilots having acquired most of their experience in a different rescue environment. Furthermore, the multiple-goals, which the flight captain had to resolve and the compliance of the regulatory attenuated its own capacity to respond.

Another aspect of the Viable System Model, that may have implications for safety management, regards the design of information channels and transducers between the management–operation units and the environment. An information channel is characterized by its 'capacity' to transmit information, which should be higher that the amount of information generated in

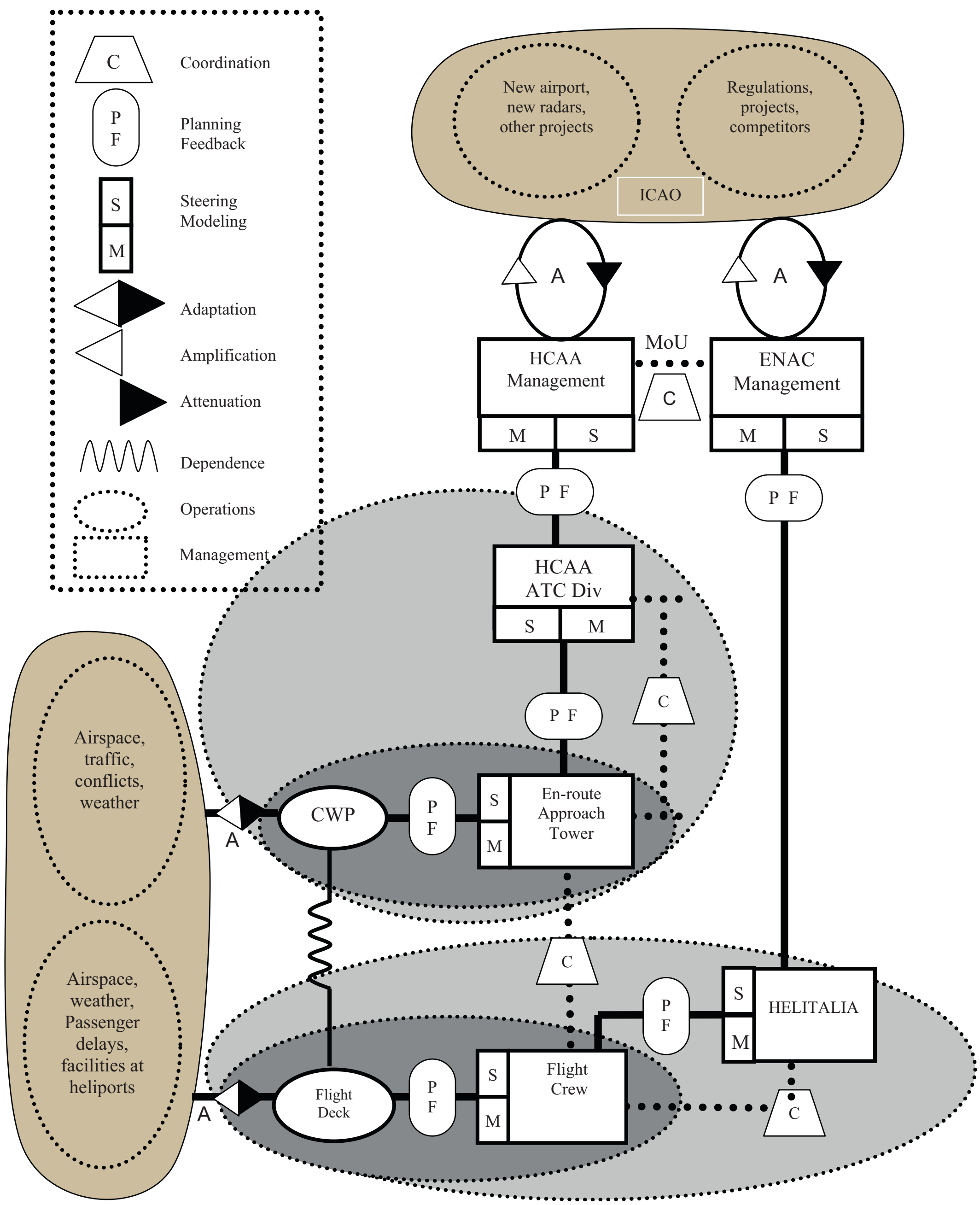
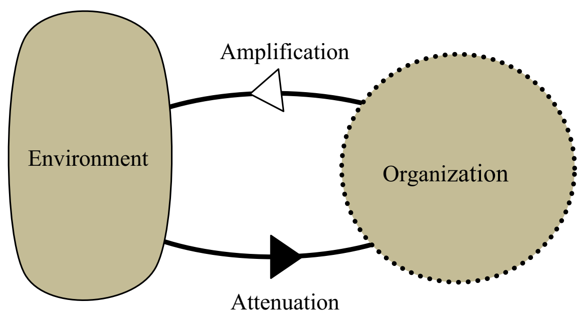


Fig. 5. A recursive representation of the wider organizational context (VSM perspective).

that time by the originating system (i.e., the second principle of organization). For instance, all information generated in the ATC system must be so 'structured' as to be transmitted to flight crews without ambiguities and unclear instructions. Wherever the information carried on a channel crosses an organizational boundary (e.g., from supervisors to workers), it undergoes transduction. A transducer might be a procedure or instruction leaflet that would 'transduce' between the person making up the rules and the practitioners who have to apply them. This is the third principle of organization stating that "the variety of the transducer must be at least equivalent to the variety of the information channel that crosses the boundary" [5]. Hence, the procedures that carry instructions from designers and supervisors should be comprehensive so that no information is lost or misunderstood by the workers. These principles of organization have been applied in the accident analysis to provide a useful basis for looking into information transfer problems across organizational boundaries.

The main VSM principles that have been reported here and in Section 2.1 are summarized in Table 5 in order to provide a basis for diagnosing organizational breakdowns in accidents. The last principle organizes several principles from general systems theory [32] and refers to the tendency of organizations to move into two different safety management approaches. The preventive approach relies on risk anticipation and exploitation of existing rules whilst the recovery approach empathizes recovery from errors, learning and mitigation. Prevention focuses on the removal of obstacles by seeking a safe environment, specializing in a narrow niche (i.e., over-specialization in Wildavsky [32]) or minimizing spread



Amplify variety of environment

- Having to cope with a wide range of weather and wind conditions
- Having to cope with low visibility conditions and elevated terrain
- Carrying critically ill passengers
- Landing in ill-equipped heliports

Amplify variety of organization

- Using highly-equipped helicopters
- Having an aircraft on readiness
- Calling for assistance navy warships to increase the organizational boundary
- Familiarity in working together in many missions (i.e., collaboration)

Attenuate variety of environment

- Improving facilities at heliports and airports
- Minimizing delays that require rescheduling of operations
- Reducing uncertainty in weather reports

Attenuate variety of organization

- Imposing rigid procedures that constrain innovation and adaptation of workforce
- Removing intelligent functions from workforce to agencies and consultants
- Relying on general skills without additional training in a diverse range of flight conditions

Fig. 6. Balancing the varieties of organization and environment.

Table 5
An overview of the main VSM principles to diagnose organizational breakdowns.

Recursion/fractal structure	Each sub-system is a viable system on its own, is embedded in larger viable systems and is regulated by the same five functions; complex behavior emerges from simple rules or functions that are repeated across all levels
Self-regulation and autonomy	Sub-systems can remain 'self-regulated' or autonomous units as long as they do not threaten the viability of the whole organization; the conditions on which autonomy is forfeit need to be agreed
Local coordination versus centralized control	Local coordination can minimize fluctuations in unit interactions but may also lose sight of overall standards and plans (i.e, sub-optimalization) ; hence, it must be balanced with central control
Circular processes of monitoring and planning	Monitoring of performance is linked to accountability that, in turn, feeds to planning and allocation of resources; planning is used to set up performance measures for monitoring
Interaction between structure and strategy	Decision making is a multiple-level activity that is built up throughout the organizational structure as a series of negotiations between levels
Adaptation	Organizations should adapt to the changes of the environment by changing their structure and strategy
Requisite variety	The variety and competencies of the organization should be matched to the complexity and variability of the environment
Boundaries	Boundaries may change the exchange rate and transduction of information channels; they may affect the visibility of other units and the degree of sharing information across boundaries
Exploitation versus exploration	Exploitation that is based on existing rules and practices must be balanced with exploration or creation of new rules (i.e., an important function of system 5)
Prevention versus recovery	Prevention focuses on the removal of obstacles by seeking a safe environment, specializing in a narrow niche or minimizing spread of danger; recovery emphasizes learning from errors and mitigation by relying on teams, making use of multiple resources via many routes

of danger (i.e., segregation or separability); recovery emphasizes learning from errors and mitigation by relying on numerous interacting actors who are making use of multiple resources via many routes (i.e., the high flux and omnivory principles, [33]).

Probably the greatest contribution of the VSM analysis regards the patterns of breakdown that resulted in a series of control flaws as identified in the STAMP analysis earlier. Patterns of breakdown tend to recur in the organization and can be seen from the analysis of a large sample of near misses rather than a single accident. The VSM analysis provides a good basis for integrating several patterns of organizational breakdown that have been reported in the literature [23,27,28]. This effort has been undertaken in Table 6, where several patterns of breakdown are identified and discussed mainly for the first HEMS accident.

The following sub-sections show a comparative analysis of STAMP and VSM approaches to accident investigation. In general, they show how the VSM analysis can be used to look deeper into the control flaws identified earlier in Section 3 with the use of STAMP. For instance, inadequate decisions and control actions can be explained in terms of several patterns of breakdowns (the VSM analysis) such as focusing on fire-fighting rather system causes, collapsing systems 3 and 5 into one unit, specializing on a narrow niche of operations and progressively being committed to the flight plan (see items from #5 to #8 in Table 6). The introduction of the category of adaptation offers new ways of understanding patterns of organizational analysis and learning that have not been addressed in STAMP analysis. Finally, the three principles of organization have also been used to highlight flaws in mental models, coordination and workarounds in implementing actions (see items #2, #10 and #13, Table 6).

4.1. *The crew performance*

VFR flights into IMC are often characterized by pilot decisions to continue flights into adverse weather despite having been given information or presented with cues, indicating they should do otherwise. This continuation of one's original plan, even with the availability of new evidence suggesting that the plan should be abandoned, has been termed a *plan continuation event* (PCE, [34]). The STAMP analysis has traced the causes of the plan continuation error into the mental model flaws (e.g., lack of crew experience in adverse weather) and ambiguous weather information. This is the 'situation assessment' hypothesis [35], where pilots may risk 'pressing on' into deteriorating weather because they do not fully realize they are doing so.

A deeper insight into the decision to continue the flight in adverse weather can be gained using the VSM model to look into the planning and steering aspects of crew performance (e.g., how crew change their plans over time and what organizational pressures affect them). The control system 3 of VSM is concerned with the evolution of plans over time as well as the motivational aspects of planning (#7, Table 6). It is likely that the captain kept 'pressing on' into deteriorating weather as the flight progressed because of the 'sunk cost' effect (i.e., amount of effort invested in the flight) and the social and organizational pressures involved. This is known as 'progressive commitment', which is more likely to be brought into play in situations where the location of adverse weather is close to destination and the condition is evolving or deteriorating and where the stakes are very high [36]. In the first HEMS accident, the 'progressive commitment' hypothesis seems very likely especially due to social pressures (i.e., the HEMS flight was carrying a critically ill passenger) and organizational pressures (i.e., captain was the most experienced pilot in the company).

Another example of organizational pressures was that the chief pilot, who was also the captain in the first accident, was sharing its time between Italy and Greece and juggling between the flying and the managerial tasks of its second assignment as a flight operations director. Although the practitioner's highest goal may be related to safety, there are also other administrative goals that may be less explicitly articulated, which impact pilot decisions and interventions (#5, Table 6). Flights in adverse situations impose great demands on pilots who are expected to invent sophisticated strategies to adapt to new situational demands. However, cultivating resilience may be disrupted by other business constraints that limit the amount of practice and on the job experience. In cybernetic terms, this implies a collapse of the meta-system since the functions of system 5 (i.e., company flight director) are collapsed into the functions of system 3 (i.e., the flight crew). When the person for company planning and oversight is the same with the one responsible for performing flight duties, then system 5 cannot respond proactively whilst system 3 may lose its level of competence.

Table 6
Some performance breakdowns leading to control flaws and hazards.

Mental models—modeling 1. ATC models of HEMS problems were incomplete, leading approach control to under-estimate the risk for the HEMS flight 2. HCAA regulatory models did not compare how new and older HEMS balanced variety in organization versus environment (i.e., a failure of 1st principle of organization)	**Attentional control dynamics—monitoring** 3. Information handling in approach control was hindered by poor coupling of ATC monitoring and crew planning and expectations 4. ENAV regulatory problem detection and monitoring was displaced by norms of respectful behavior towards HELITALIA (propriety)
Steering of control algorithms 5. Sharing between flight and administrative duties resulted in goal conflicts and a collapse of systems 3 and 5 into a single metasystem 6. Problems in the organizational structure (HELITALIA) resulted in fire-fighting, due to poor organizational learning (of system 4)	**Planning of control algorithms** 7. Plan continuation errors in the cockpit may relate to progressive commitment and loss of situation awareness 8. Procedures and training in HELITALIA were specialized on a narrow niche of operations (not covered adverse weather over Aegean sea)
Controlling coordination of decision makers 9. Control structures joined highly in the hierarchy (i.e., HCAA and ENAV) may increase wrong assumptions about allocation of responsibilities 10. Critical information was not properly structured or transmitted with ambiguities to helicopter (i.e., a failure of 2nd principle of organization)	**Adapting coordination to environmental demands** 11. Neither the benefits of a mixed fleet nor the resilience of the older loosely coupled organization were noticed by the flight company 12. HCAA learning from events was impeded by the slow dynamics of the accident investigation loop (e.g., data collection, analysis, validation, dissemination)
Implementing actions and workarounds (Only for 2nd **and 3**nd **HEMS accidents)** 13. Crew took a visual shortcut (e.g., second HEMS accident); workarounds cannot be audited in formal organizational channels (failure of 3nd principle of organization)	14. Crew optimized locally by continuing flight into a degraded mode (e.g., third HEMS accident) that escalated during the flight (sub-optimalization)

4.2. Organization of the flight company

Night-time VFR is an acceptable and regularly compliant form of operation worldwide that is endorsed by ICAO. The concept is not intended for revenue flights but rather aims to fill-in gaps by acknowledging social needs in the form of HEMS and Search and Rescue operations. Given the social necessity of HEMS operations, the increased risk of night VFR flights is formally accepted. For this reason, the crews should have accumulated a lot of domain-specific experience in terrain awareness, aircraft performance and human factors or fatigue matters. General flight experience may not be an essential prerequisite for tactical and mental agility. According to STAMP analysis, an important factor in all accidents was the selection of flight crews with a narrow experience in night VFR operations. Similarly, the VSM analysis found that crews were over-specialized in medical-transfer flights over land and hence their expertise kept growing in one direction only (#8, Table 6). This over-specialization usually renders aviation systems unstable, allowing little scope for resilience [29]. According to cybernetics, the hallmark of operational agility for an HEMS organization is to operate effectively across the full range of operations. This can be achieved by encouraging practitioners to improve their self-referential assessment and by enriching procedures with experience in local conditions (e.g., adverse weather, gusty winds in Aegean, using poorly equipped forward bases).

The STAMP analysis indicated that supervision and monitoring of flights were inadequate since the flight operations director and the senior flight officer were both absent from the OCC as they had other pressing flight duties. Hence, HEMS flights relied on college graduates with little experience and low status for managing operations under time pressure. To probe into these inadequacies in monitoring and control actions of the flight company, the VSM has been used to look into how organizations are structured to hear and respond to safety concerns. This prompted the authors to collect additional data on the performance of system 4* for organizational learning [6]. It appeared that there have been many pilot reports about certain organizational omissions (e.g., communications were made on cell phones rather than nominal air to ground and ground to ground VHF or UHF networks) but the persons tasked to respond to such messages were inexperienced or busy with flight duties. Many work obstacles were removed by well motivated employees without bringing them to the attention of the high-level organization. This organizational structure resulted in a fire-fighting strategy where local teams were left on their own to resolve local problems whilst systemic causes remained unattended (#6, Table 6). Information about safety problems just dissipated through the organization because there was nowhere for it to go. As a result, the same problems tended to repeat, as no learning was taking place, which increased the chances of an incident in the near future.

4.3. Communications with air traffic control

Abnormal situations triggered by adverse weather create a data-overload problem, which increases monitoring requirements. ATC controllers may be busy in coping with aircraft on holding but they should keep looking for new information and new priorities for action (e.g., deal with the HEMS helicopter in an adverse weather environment). As shown by the STAMP analysis, coordination among all ATC units was rather fragmented; transfer of information was very intense without a clear indication of who and when should use this information about the flight of the HEMS helicopter. The VSM analysis uses the second principle of organization to examine how the ATC system structures or processes all information generated about air traffic and how it is transmitted to the HEMS crew without ambiguities and omissions. A failure of this organizational principle (#10, Table 6) seemed to cause some sort of 'information garbling', which is indicative of poor coordination such as unclear roles and responsibilities over time, unclear plans of conduct of operations and poor procedures for communications.

In addition, the approach controller had difficulty in remaining sensitive to subtle events that occurred at disparate times in the environment (e.g., HEMS crew calling him at irregular times). The STAMP analysis indicated that the approach controller did not manage to update the HEMS crew on the seriousness of the weather condition. Ultimately, monitoring of the HEMS situation is related to the mental models and perceptions maintained in the aviation community. Although HEMS operations are one of the riskiest segments of aviation, HEMS helicopters are not formally required to carry Flight Data Recorders (FDRs) and Cockpit Voice Recorders (CVRs), which minimizes their electronic footprint in accident investigation. This failure to recognize the risk levels of HEMS flights has been cascaded down through other organizational levels, including ATC services. The authors carried out several informal interviews with controllers, which showed that they tended to regard HEMS flights as a burden that adds to other scheduled commercial flights and increases their operational complexity (#1, Table 6).

According to the VSM analysis, another cause of the risk misperception may relate to the breakdown of basic coupling between the processes of ATC monitoring and crew planning. According to ICAO regulations, controllers should closely monitor HEMS helicopters in adverse flight conditions and give them a higher priority to other traffic. On the other hand, the planning to continue or abort the flight to the final destination rests with the flight crew. It is plausible that the approach controller maintained a "specious" self-serving justification for his pre-occupation with the high altitude traffic that were on holding (#3, Table 6). This norm of conduct has completely decoupled monitoring and planning between controllers and crews, respectively, and prevented a heedful inter-relating between the two sub-systems. This decoupling factor may seem to explain the STAMP finding about the wrong expectations of the crew to rely on controllers to alert them when to abort the flight. Busby [27] also observed this 'speciousness' factor in his analysis of a SPAD accident (signals passed at danger) where train signallers attributed complete responsibility for SPADs to the drivers who went through the red light.

4.4. Oversight by regulatory authorities

Inadequacies at the regulatory oversight and monitoring had also an impact on the three HEMS accidents. The new HEMS organization (i.e., HELITALIA) was accountable to both ENAC and HCAA since the helicopter fleet was registered in Italy but operated in Greece. The primary technical and operational audit would be undertaken by ENAC while a second layer of monitoring by HCAA would ensure that ENAC's audits were taking place as agreed. However, two months after the first accident, the Memorandum of Understanding (MoU) between the two regulatory authorities had not been formally signed. In addition, any inadequacies in the administration of flight operations were explained away by HELITALIA since a supplementary contract allowed the operations to start even three months prior to the activation of the formal contract. It appears that the flaws in the coordination between ENAC and HCAA at the regulatory level allowed several latent causal factors to exit in the organization and supervision of HEMS flights. This finding has been supported by both STAMP and VSM analysis. Accidents are most likely in boundary areas or in overlap areas where two or more actors control the same process or processes with common boundaries [37]. The functions in the boundary or overlap areas are often poorly defined, which leads to confusion over who is actually in control, which may result in wrong assumptions. Furthermore, the higher the controlling organizations from the sharp-end the higher the chances are that some wrong assumptions will be made with regard to allocation of role responsibilities (#9, Table 6); the higher one gets at the organizational level the greater the demands in managing variety.

Even after the first accident, the Italian regulatory authority (ENAC) did not seem to increase its monitoring of HELITALIA probably because the report into the accident was still pending. On the one hand, this norm of conduct is normal since a regulatory authority cannot make any judgments when the implications of the first accident remain unclear. On the other hand, the flight company and the aviation system were left in a vulnerable conditions as the systemic causes that contributed to the first accident were still in play, hence laying the conditions for another accident (#4, Table 6). Indeed, this proper way of doing business turned to be very problematic since the second and third accidents that followed in a short time interval.

Finally, the STAMP analysis found that a few control flaws of Greek regulatory authority (HCAA) in the conduct of safety audits of heliports and operations of the flight company. Although STAMP prompts analysts to examine the perception and mindset of regulators related to how effective and safe operations are made, little guidance is offered how to do so. Probably the earlier discussion on balancing the varieties of the organization and the environment (i.e., a failure of the 1st principle of organization) provides a better basis for looking into the mindsets of regulators following the successive operation of the earlier HEMS civil and military organization. New organizations that take over a successful concept of operation do not attract the attention of regulators because maintaining a good safety record is thought to be an unproblematic task that can be sustained with minimal effort and adjustment. The assumption is that best practices and operational procedures can transfer to new organizations with minimal intervention on the part of the regulator (#2, Table 6). This assumption may be true when the new organization adopts similar concepts of operation in a static world. In our case, however, the new organization displayed significant divergence from earlier models of operation and was reluctant to make the necessary commitments and resources. In all three accidents, regulatory oversight can be best described as degraded and out of focus. At the regulator level, no one anticipated the speed and severity of the escalation pattern of the three accidents; each one was perceived as a single non-repeatable case of an unwanted stochastic fit.

4.5. *Failures of adaptation and organizational learning*

Organizations at different levels should show adaptation in their operations to respond to new environmental demands and learn lessons from failures to meet them. This section looks into the failure of HELITALIA to adapt its organization to the demands of the new aviation environment in Greece as well as the failure of HCAA to learn from experience and control the incident investigation process involved in the HEMS accidents. As shown in Fig. 6, the concept of operation of the older HEMS organization was quite successful with a good safety record. Although not designed originally for this purpose, the older concept of HEMS operations that was based on military aviation and the flag carrier (OA), provided the required organizational agility. It can be regarded more as an ad-hoc serendipity adaptation that proved successful through time than a well-prepared plan from a central authority. Fundamental to its success was that personnel had developed a successful self-referential assessment on how safety can be maintained through a diverse spectrum of operations. This success however played its role in effectively masking many complexities and normalizing the safety requirements for transitioning to a new HEMS organization (#11, Table 6). It was thought that any new organization could easily accommodate the HEMS operational demands by building on the best practices and the experience of the earlier successful concept of operation.

The accident investigation reports represented the culmination of industry-wide beliefs of a thorough examination and a deeper understanding as to what really happened and most importantly, what went wrong. The release of an accident investigation report is surrounded by an euphoria of having an informative explanatory value for the whole industry. One of the core assumptions related to the control loop of incident investigation and to the adequacy of available time (#12, Table 6). It is assumed that after an accident, sufficient time is available to complete the investigation process, formulate the lessons-to-be-learned, disseminate information to stakeholders and allow the industry to prevent analogous accidents. In cybernetics terms, the scanning process of threats and risks in the environment is undertaken by system 4 on the basis of an updated mental model of the internal organization. It seems that the inability of the regulatory authorities (i.e., HCAA) to maintain an accurate model of the new HEMS organization (#2, Table 6) has led to a sluggish system 4 that did not realize that delays in the incident investigation would leave the new HEMS organizations in a vulnerable situation; the same systemic causes were still in play during the long investigation period and led to a second and a third accident.

4.6. *Workarounds in the control actions contributing to other accidents*

In the second accident, the helicopter crashed on the top of a mountain a few moments after departing from a non-supervised heliport, when the flight crew performed a visual shortcut at night over elevated terrain. According to STAMP, this is an example of inadequate control action where the flight crew relied on their own *heuristics* or *workarounds* when flying close to elevated terrain in order to avoid further delays. But why do crews resort to workarounds? To understand this issue, the analysts need an organizational model that examines the transducers between management and operation units as well the constraints of work that impinge on human performance. According to VSM, a flight procedure can be thought of as a channel that transduces between the management unit making up the rules and the operational crew who have to apply them. Transducers or flight procedures, may protect crews from obstacles in flights, but are lengthy and time consuming for a full scale execution. Crews resort to workarounds, which may remain safe as long as certain conditions prevail (e.g., ATC supervision of heliport, good meteorological conditions etc). However, knowledge of workarounds and pre-conditions cannot be fully transduced into written procedures without a formal safety assessment (#13, Table 6). In a sense, the variety of the transducer (i.e., the procedure) is usually lower than the variety of the channel between designers and practitioners (i.e., a failure to meet the third organizational principle). Better management attitudes towards workarounds would include them in formal safety assessments so that their insights are gleaned and transduced into formal procedures.

In the third HEMS accident, a helicopter flying VFR at night crashed into the sea during the final stages of the approach for landing. Although the report traced the causes into a misdiagnosed electrical failure in the final stages of the approach, it seems likely that the crew was aware of the problem at the early stages of flight but tolerated the problem, which later escalated into a major one. According to STAMP, it seems that the crew had an incomplete mental model of the problem but it is difficult to explain why this was the case. In HEMS operations, flight crews may choose to flight in a degraded mode (i.e., flying with a minor problem) because grounding the helicopter for maintenance in a remote island would create tremendous delays. Such work-arounds often lead to a misconception of operational agility, which hides the boundaries of safety. Knowingly flying in a degraded mode (i.e., tolerating a malfunction) is a non-compliant behavior that could optimize locally but may lead to a disaster when the degraded mode escalates in the course of events. The sub-optimalization principle [32] of cybernetics (#14, Table 6) may provide a better explanation of the traps involved in knowingly flying in a degraded mode.

5. Conclusions

This article has attempted to bridge the gap between two parallel trends in systemic accident models. On the one hand, accident investigation techniques (i.e., AcciMap and STAMP) have been developed that looked into flaws of control processes and problems in enforcing constraints between different levels in the organization. On the other hand, as seen in Section 1, a large literature of patterns of breakdown was developed in an effort to apply organizational models to specific accidents. To help accident investigators to look at both the control flaws and organizational breakdowns of accidents, a link was established between a control theoretic accident model (i.e., STAMP) and a cybernetic model of organizational viability (i.e., VSM).

The proposed joint STAMP–VSM framework relies on a refinement of control categories of STAMP (e.g., steering and planning of control algorithms as well as adaptation to the external environment) so that the VSM functions can be mapped onto the STAMP analysis of organizational structures. Second, a recursive representation of organizations was proposed that has several advantages over the hierarchical representation (e.g., the same organizational principles apply at different levels). The recursive structure may help analysts to rethink the safety organization, model new information loops, identify new constraints or see problems in the adaptation and steering functions of the organization. In addition, the 'recursive structure' can provide insights how to "unfold complexity" into several organizational levels—e.g., some of the complexity can be managed by the intelligent behavior at the operational level and the remaining problems (sometimes called residual variety) can be mopped up by the senior management levels. From the case study, it appeared that the recursive analysis may be more difficult to apply from start without a preliminary analysis of the functions and interactions of the constituent sub-systems. In fact, once a hierarchical analysis is made, the analysts may select particular areas to probe into by means of a deeper recursive analysis. Therefore, the transition from a hierarchical to a recursive representation is not so difficult to make. A recursive VSM analysis focuses on the organizational structure rather than on single actions and events; as a result, the VSM analysis is usually performed for the organization of safety management and can be used for the investigation of all accidents in the same organization. Once a VSM analysis has been performed, it can provide useful analysis for several near miss and accidents. Dijkstra [14], for instance, has been working towards a general aviation structure for the analysis of all accidents in the same domain.

Third, the three VSM principles of organization provide another view of organizational interactions regulated by the processes of attenuating and amplifying variety to manage complexity. Information channels crossing the boundaries of sub-systems can be studied from the perspective of their capacity to transmit information and transform it with the use of several transducers (e.g., oral instructions, written procedures, shiftover protocols etc). Fourth, the organizational cybernetic model (VSM) allows analysts to bring together several issues of organizational theory that relate to 'self-regulation', the autonomy–control dilemma, prevention versus recovery and the interaction of structure and strategy (see Table 5). The latter is very important in the management of change since strategy should be built-up throughout the organization and take into account the needs and interests of all sub-systems. In this sense, many failures to improve a safety policy could be traced into problems of taking on board the views and interests of practitioners throughout the organization. Finally, the proposed framework addresses how organizations adapt to challenges in their environment by amplifying their own variety or by attenuating the complexity of the environment. Adaptation failures may explain why the new HEMS organization did not see that a mixed fleet and a capacity increase in night-time VFR flights were necessary for managing the complexity of the HEMS environment.

From this discussion, it appears that STAMP analysis should proceed the VSM analysis as the former provides a description of control flaws that can be explained in terms of the five organizational functions and the three principles of organization. In fact, the analysts have a choice with regard to the depth of analysis required; some control actions or monitoring functions can be sufficiently covered by STAMP without any need to look deeper into their underlying breakdown mechanisms. Furthermore, the VSM analysis can be made proactively as part of an organizational audit on the basis of early warnings from near misses and previous incidents. In this sense, VSM can provide useful information about safety management to the STAMP analysis.

The analysis of the case study indicated that the joint STAMP–VSM framework is quite effective in bringing into the fore several patterns of breakdown at the organizational and regulatory levels. There is still, however, a dependency on the literature of organizational breakdowns that have been revealed by earlier studies [23,27,28]. It may be rather difficult for an accident investigator to rely solely on the proposed framework without any prior knowledge of the literature on organizational breakdowns. Overall, the framework can help analysts to model the complex interactions across boundaries, the information structures that impede communications and the delineation of responsibilities across multiple controllers. Awareness of these traps can help organizations avoid them or at least decrease their negative impact.

A critical question in the use of the joint STAMP–VSM framework is whether its application should direct the formal investigation or should follow and enhance the findings of the official report. Other studies that applied systemic methods (e.g., STAMP and AcciMap) in accident investigation [38,39] have found that it is difficult to use them as primary tools to manipulate primary evidence into a coherent analytical framework. In many accident investigations, systemic techniques have relied on existing official reports to provide further insights. However, there is a need to make systemic methods more proactive so that they can guide the formal investigation and highlight critical organizational problems that may continue to threaten safety during the investigation period. In our case study, it became evident that the standardization of formal investigation practices took a very long time, hence leaving a set of latent organizational conditions still into play for another catastrophic event before the conclusion of evidence. The requirements for reliable information from FDRs, CVRs and ATC transcripts that represent the 'electronic footprint' of an accident, the focus on the chain of events and the accountability of practitioners and the procedures for the dissemination of information to the stakeholders are very time-consuming; hence, organizations remain vulnerable to the same conditions that created the damage in the first place. Although investigation boards should comply with formal requirements, the need for a fast identification of control flaws in the organizational structure is of paramount importance. It is hoped that the VSM analysis can make the systemic methods more proactive because VSM focuses on the organization of safety management, which can be described on the basis of earlier near misses and minor incidents. A VSM analysis can be made as part of an organizational audit to enhance efficiency and safety; hence, general patterns of breakdown can be identified prior to a serious accident.

Another critical question in accident investigation regards the costs of using the proposed hybrid approach as many organizations have placed cost caps and time limits on the investigation process. It is anticipated that the joint STAMP–VSM analysis may impose a high cost toll when applied retrospectively. For this reason, it is important that the VSM analysis is done as part of organizational audits and change management programs so that a major part of the analysis of safety management is already completed to provide information to the accident investigation. When used proactively, the joint STAMP–VSM framework can also take on board the views of sharp-end practitioners and supervisors who may be more willing to volunteer their knowledge as part of an organizational audit rather than as part of an accident investigation. In our case study, we were fortunate to have access to several air traffic controllers who offered valuable insights that were difficult to capture even with the proposed methods. In this respect, the present analysis should score high in replicability as it reflects the views of many practitioners in the application domain.

A final remark should be made about the potential of the joint STAMP–VSM model to incorporate modern ideas from complexity theory. Admittedly, VSM has been one of the hard systems methodologies that offer little flexibility in describing organizations and this has been criticized in the systems literature [40,41]. For instance, the recursive structure of VSM assumes that the five functions are equally applicable to all levels in the organization. This may apply to safety-critical industries that rely on formal organization and hierarchical controls; in contrast, small-to-medium size industries in lower risk domains could be more flexible with their organizational functions. In fact, some applications of complexity theory to accident analysis and crisis management [42,43] have used more flexible descriptions of organizations and advocated that structures and functions can emerge in different shapes. It is proposed that the pre-defined VSM functions are seen as high-level descriptions of the requirements of control rather than as recommendations of how organizations should control their functions. Further research should examine how to relax the requirements of VSM analysis to allow more flexibility in adding or removing functions for different organizations.

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