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ORIGINAL RESEARCH

How a cockpit calculates its speeds and why errors while doing this are so hard to detect

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Abstract Recent incidents have shown that the production of take-off speeds is an activity vulnerable to miscalculations with a potential for disastrous outcomes. The aim of this paper is to analyze the calculation of the take-off speeds in a modern airline cockpit as a distributed cognitive activity in order to identify possible vulnerabilities in this process. We took the cockpit as the joint cognitive system under analysis and conducted an ethnographic study based on documental analysis, flight observations, interviews, and the analysis of 22 events involving failures related to the calculation of take-off speeds. The main argument is that the cognitive systems engineering perspective, with less focus on the human contribution than it is common in investigations, levels people and artifacts in the system as equal contributors to its eventual performance. Our analysis identified four assertions regarding vulnerabilities in the process of take-off speeds calculation: (1) representations at the level of the cockpit are always partial and incomplete; (2) some interactions require interpretation rather than institution; (3) interactions of agents do not follow a canonical process of coordination; (4) the control of the prevention of failures is accurate but inadequate. These vulnerabilities are a matter of interactions among cognitive systems in the cockpit, rather than vulnerabilities of individual agents, such as humans or artifacts.

Keywords Joint cognitive system · Cognitive systems engineering · Representations · Interactions · Coordination · Control · Aviation

1 Introduction

Fifteen years ago, Ed Hutchins published a paper under the title "How a cockpit remembers its speed" (Hutchins 1995a). It was an important salvo in what has become known as the second cognitive revolution of the twentieth century. The first cognitive revolution, roughly from the 1950s to the 1970s, was largely a reaction to behaviorism that had kept the mind locked up as a "black box" (Neisser 1976). This first revolution, however, equated cognition and the construction of meaning with the processing of information by a mind separated from the world, a metaphor inspired by contemporary technology (radio, then computer). Hutchins (1995a) validated the theoretical approach of the cognitive system as the unit of analysis, by considering the cognition situated and distributed in the interactions among humans and artifacts. Hence, the idea was that an entire cockpit that remembered its speeds for landing, not just the individuals (pilots) in it.

Recent serious incidents in aviation have shown that the production of airspeeds in an airliner cockpit, regarding take-off, is an activity vulnerable to interruptions and miscalculations (Australian Transport Safety Bureau 2009). In spite of Hutchins' work and the second cognitive

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revolution, such incidents are often reduced to (supposed) cognitive or motivational shortcomings in individual minds (e.g. loss of situation awareness or complacency), and recommendations from investigations into such a kind of shortcomings can end up focusing on the improvement of individual pilot skills, rather than understanding the situated and distributed cognitive system that was responsible for the production of airspeeds for take-off.

In this paper, we analyze the calculation of take-off speeds in a modern airline cockpit as a distributed cognitive activity. The aim is to better identify the possible vulnerabilities that it is exposed to, particularly given the introduction of new technologies supporting this task. We have premised the production of take-off speeds as a "calculation" because it involves the manipulation of several input parameters in order to get the output values required for operation. Today's activities surrounding the calculation of airspeeds involve computer technology of a generation beyond what Hutchins described in his 1995 paper, particularly the flight management computer (FMC).

We aim at showing that a Cognitive System Engineering (CSE) perspective, with less focus on the human than is common in investigations into take-off speed incidents, levels people and artifacts in the system as equal contributors to its eventual performance. CSE studies the goal-oriented interactions of people and artifacts in order to produce work in a certain context (Hollnagel and Woods 1983; Hutchins 1995a, b; Woods 2003; Woods and Hollnagel 2006; Woods et al. 2002). CSE assumes that each activity carried out by the cognitive system is, at the same time, cause and consequence of the system's performance. The way people and artifacts interact while accomplishing tasks creates representations in the system, which provide plausible outcomes of good and poor performance.

The last 15 years have seen an extension of the ideas on distributed cognition, with concepts such as interactions (co-agency and coordination), control, and resilience gaining ground in the various models that have been proposed since Hutchins published his seminal work (1995a). We assess the calculation of take-off speeds in the light of such recent additions to the distributed cognitive vocabulary and assess the analytic usefulness of those concepts. The point we wish to make in this paper is not about whether the aviation investigators' conclusions or recommendations are right or wrong, but about the usefulness of a joint cognitive system approach to understand the interactions and vulnerabilities in a complex activity like the calculation of take-off speeds.

2 Empirical investigation and data analysis

We adopted a qualitative approach using ethnographic methods (Flick 1998; Hutchins et al. 2002). Four data collecting strategies were used from March 2009 to February 2010: (a) documental analysis; (b) in-flight observations of line operations and flight simulations; (c) interviews with pilots; and (d) analysis of incidents and accidents involving the calculation of take-off speeds.

The documents analyzed consisted of (1) airplane flight manuals (AFMs) of the Boeing 737-NG, Airbus A319/320/321, Embraer ERJ 190/195, (2) Standard Operating Procedures (SOPs) of five major air carriers, (3) manual of three laptop tools (Boeing Laptop Tool (BLT), Airbus Less Paper Cockpit (LPC), and Embraer Portable Operational Package (EPOP)), and (4) technical documents related to the calculation of take-off speeds and related incidents from two manufactures (see Airbus 2004a, b, 2005; Boeing 2000, 2007). These documents contributed specifically to the understanding of the prescribed procedures associated with the calculation of speeds for take-off.

Observations of 22 pilots during training sessions in a Boeing 737-700 simulator, as well as 2 in-flight (line) observations in a major airline, were carried out. Two of the flight simulation sessions were recorded in order to facilitate the description and analysis of the work domain. During these observations, the research team looked for a better understanding of how pilots are applying the prescribed procedures and discuss the possible vulnerabilities that come with it. It is relevant to report that two members of the research team have experience as airline pilots, which facilitated the ethnographic approach.

The open-ended interviews were held with 13 airline pilots from major carriers, of which six were captains (including three technical pilots) with more than 10 years of flight experience and seven were first officers with more than one but less than 5 years of flight experience (in various types of aircraft: Boeing 737/747/777, Airbus A319/320/321, Embraer 190/195). The interviews were used as a manner to identify pilots' approach to the calculations of take-off speeds and to discuss the preliminary findings from the preceding documental analysis and observations. These interviews took about 2 h and were performed in a Flight Training Organization in order get a better comprehension of the interactions among pilots, artifacts and procedures in the cockpit.

Analysis of situations involving take-off speeds calculation using incident and accident databases revealed 22 occurrences since 1991. Rather than an exhaustive list of this type of events, the information for these databases was provided by legal authorities for public consulting and should thus not be considered as the total number of incidents during this period.

Tail strikes followed by aircraft damage, however, no injuries to persons on board, were the outcome of 45.45% ($n = 10$) of incidents. In 27.27% ($n = 6$), there was no technical or operational consequence. In 13.63% ($n = 3$), the safety margins were reduced, while in 9.09% ($n = 2$), the crew were able to reject the take-off. Only one runway excursion happened. Among those situations, there were 72.72% ($n = 16$) of incidents with minor damages and 27.27% ($n = 6$) of serious accidents.

Given the difficulty of extracting reliable and falsifiable data from dynamic processes (Christoffersen and Woods 2003; Woods 1993), we developed the following protocol for the analysis of cognitive work: (a) the description of why the cockpit needs to calculate its speeds; (b) the definition of a typical course of action; (c) the delimitation of the joint cognitive system under analysis; and (d) the analysis of joint cognitive properties of the system related to its performance.

The analysis of joint cognitive proprieties of the system is described by means of four questions: (a) how is the cockpit representation formed? (b) What are the main types of interactions among people, work, and artifacts in the cockpit? (c) How is the coordination performed during take-off speeds' calculations? (d) How is the control of the activity realized? In order to answer these questions, we used empirical findings from observations, documental analysis (including database reports), and interviews. Moreover, these data were supported by related literature review. Based on all the data collected, we discussed why errors in the calculation of take-off speeds are not easily detected.

3 Why does a cockpit need to calculate its speeds?

A large system involving pilots and flight dispatchers, as well as many technological artifacts, is responsible for determining the correct take-off Gross Weight[1] (GW) of the airplanes and its related take-off speeds, the so-called V-speeds: V1[2] (Decision speed), Vr[3] (Rotation speed), and V2[4] (Safety speed). Each of these V-speeds has technical and procedural consequences for a safe take-off and climb of the airplane.

If the calculation of the correct V-speeds fails, two consequences are likely to occur: (a) too high take-off speed values will result in more runway distance for take-off, but often with little implications for safety; (b) too low take-off speed values will lead pilots to prematurely commence lift-off, which will also increase runway distance for take-off, and might even cause an excursion, due to the incapacity to lift-off. Another typical outcome in the situation of too low V-speed values is a tail strike.

Tail strikes occur when the airplane's tail touches the runway during take-off or landing. It can significantly damage the airplane and therefore be considerably costly for the airline. Several factors can contribute to a tail strike, most of them related to the flight crew's operating flight techniques (during take-off and landing) and airplane geometry. In the last 15 years, there have been multiple serious incidents and accidents related to improper take-off speeds calculations, resulting in early rotation at a too low airspeed for concurrent weight and flap settings.

Typical incidents involving take-off speeds calculation are not isolated and have occurred with different types of aircraft, operational conditions, and geographic regions (LAA 2008). According to the National Transportation Safety Board (2005), safety recommendations and initiatives regarding take-off speeds determination have been addressed since 1972. As stated by the Transportation Safety Board of Canada (2004, p. 53), "… there is still not a reliable in cockpit system available for crews to detect and react to abnormal take-off performance in a timely manner."

Recent incidents involving the calculation of take-off speeds, also show that different artifacts are used to perform the activity (for example, runway analysis charts or cockpit computers) and involve multiple-agent interactions (e.g. pilots, flight dispatchers, and cockpit computers). In a recent case in New Zealand, a tail strike occurred because the Vr was set 33 knots below the 163 knots required for a safe take-off, due to an incorrect assumption of the GW to be 100 tons less than the airplane actually was. A take-off weight transcription failure led to the miscalculation of the take-off data using runway analysis charts, which in turn resulted in a low thrust setting and excessively slow take-off reference speeds (Transport Accident Investigation Commission 2003).

In another event, the same type of failure caused a fatal accident with a cargo airplane in Canada. In this episode, however, instead of using runway analysis charts, the crew were performing calculations with a cockpit laptop (Transportation Safety Board of Canada 2003). Alike this occurrence, another tail strike happened in Australia in 2009 (Australian Transport Safety Bureau 2009). This serious incident is still under investigation, but preliminary findings point to the same incorrect weight and take-off speeds calculation; pilots typed a "2" instead of a "3" in the first (left) digit of the GW value, resulting in a GW 100 tones less than the actual GW of the airplane.

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[1] Gross Weight (GW), sometimes also referred as Take-off Weight (TOW) or Actual Take-off Weight (ATOW)—is the entire weight of the airplane, including fuel, passengers, and luggage. The airplane's take-off gross weight is the gross weight at the beginning of take-off and is used as the basis for the calculation of take-off speeds.

[2] V1—Take-off decision speed—is the speed during take-off for which it is the last possible moment, in the event of an engine failure or rejected take-off, to safely stop the airplane on the remaining runway.

[3] Vr—Rotation speed—is the speed during take-off at which the pilot starts to rotate to the lift-off attitude in order to start flying.

[4] V2—Take-off safety speed—is the initial climb out speed used after lift-off to achieve a certain height in a certain distance, in order to ensure adequate control and climb performance in case of an engine failure.

Table 1 Input and output information of the general processes of the take-off speeds calculations

General processes of V-speeds calculations	Input	Output
Definition of the airplane's operating weight	Basic empty weight, passengers, load, flight plan, meteorology, SOP, field limit, climb limit, landing limit	TFW, ZFW, GW → definition → Load Sheet preparation
Computation of the airplane's operating parameter	Load sheet, flight plan, ATIS	Engine Thrust Settings, Flap position, V-speeds → Take-off Data Card preparation
FMC programming	ZFW, TFW, GW, Engine Thrust Settings, Flap position, Stabtrim set, V-speeds	Final GW, Final Engine Thrust (N1). V1, Vr, V2 → PFD/MFD information
Verifications and checklist readings	Load sheet, Data card, FMC, PFD/ND, MFD/N1, MCP	Final GW, Final Engine Thrust (N1), V1, Vr, V2 → Confirmation

4 Typical course of action for the calculation of take-off speeds (with and without cockpit computers)

In a typical jet transport airplane, the take-off speeds calculation involve cooperative work of the aircrew and several other agents (such as ground staff) when performing procedures required to conduct this activity. Even though the sequence of actions may vary according to airplane type/manufacturer, airline, or contingencies of the natural work (such as interruptions and last minute changes), four general processes of take-off speeds calculation involve: (a) definition of the airplane's operating weights; (b) computation of the airplane's operating parameters; (c) flight management computer (FMC) programming; (d) verifications and checklist readings. These steps are summarized in Table 1, and described in more detail later in the text.

4.1 Definition of the airplane's operating weights

As a rule, the definition of the airplane's operating weight is related to the determination of the Zero Fuel Weight (ZFW), the Take-off Fuel Weight (TFW), and the Gross Weight (GW). The GW of the airplane is the sum of the ZFW and the TFW (which usually includes some extra weight for burn-off during taxi-out). The ZFW is determined by totaling the aircraft's empty weight (without fuel), the passengers, and the cargo load. The TFW is chosen by the aircrew considering the flight plan, enroute weather forecasts, and company standards, and refers to the total fuel on board. Performance implications, such as field limit (e.g. runway length, runway slope, wind, pressure altitude, and temperature), climb limit (e.g. rate of climb during departure and obstacle clearance), or landing weight limit, may influence the ZFW and/or TFW and consequently the GW. These weight determinations should be considered prior to the take-off speeds calculation and are usually provided to the aircrew by means of the load sheet document.

The load sheet contains the list of operating weights, taking into account previous performance computations, and is created by company flight dispatchers. As the final ZFW of the airplane depends on the actual number of passengers and load on board, preliminary values of ZFW, TFW, and GW are provided to the aircrew, in order for them to execute flight deck preparations, route planning, and FMC programming. Minutes before the departure time, the final load sheet is delivered to the aircrew, for them to do the final calculation of V-speeds and other performance parameters.

4.2 Computation of the airplane's operating parameters

The computation of the airplane's operating parameters involves manipulation of a variety of information and can be carried out in two ways: using cockpit computers or using runway analysis charts. Cockpit computers are considered the Electronic Flight Bags[5] (EFB) and are generally divided in two categories: the panel-mounted computers (such as ACARS[6] and FMC) and the laptop tools. As the

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[5] EFB—Electronic Flight Bags are devices that display a variety of aviation data or perform basic calculations (e.g. performance data, fuel calculations, etc.). In the past, some of these functions were traditionally accomplished using paper references or were based on data provided to the flight crew by a flight dispatcher. The scope of the EFB system functionality may also include various other hosted databases and applications. Physical EFB displays may use various technologies, formats, and forms of communication. These devices are sometimes referred to as auxiliary performance computers (APC) or laptop auxiliary performance computers (LAPC).

[6] ACARS—Aircraft Communications Addressing and Reporting System is a digital data link system for transmission of messages between the aircraft and ground stations.

procedures involving both of these are very similar, we will focus our description on the use of laptops in computing the airplane's operating parameters, as this is the most frequently used option by air carriers.

When using laptops, the aircrew first copies airdrome information (such as, wind, temperature, and altitude pressure) into the proper field of the flight plan paper document or data card. Even though some airlines do not use data cards anymore, it is a sheet provided to register important take-off information, still in use by many companies. Thereafter, the aircrew inserts airdrome and load sheet data in the laptop, using dropdown menus. The software then calculates take-off parameters for engine thrust settings, optimum flaps, and V-speeds, according to the information entered by the pilots. Parameters for take-off with "full" and "reduced" thrust are generated depending on the operating circumstances (e.g. runway braking action, field weather conditions). The output values presented on the laptop should then be transcribed onto the data card (when it is in use) or directly inserted into the Flight Management Computer.

Instead of using cockpit computers (such as laptops), another manner to compute the airplane's operating parameters is by means of runway analysis charts. The computation using runway analysis charts involves the selection of the proper runway chart and the manual manipulation of numeric values of flap setting, weight, temperature, and wind. From these charts, the pilots should extract take-off parameters for maximum GW, assumed temperature for take-off thrust setting, and V-speeds. The resulting values should then be transcribed onto the data card, and from this, into the FMC. Because the use of runway analysis charts involves the mental operation of numeric values by the pilots, data cards are more often used (compared with the airlines that use the laptop tools to determine these parameters) as they assist pilots' memory in these cases.

4.3 Flight management computer programming

After the computation of the take-off parameters, using either laptops or runway analysis charts, the FMC must be programmed. This programming requires several steps, such as the performance and engine thrust settings and the definition of take-off speeds.

Typical performance requires the pilots to enter the previous defined parameters of ZFW and TFW (see previous sections) into the FMC. The FMC then automatically generates the GW value, which is the basic reference for V-speeds calculation at this point. Some aircraft, equipped with later versions of FMC software, may require the pilots to input the GW value themselves.

The next step involves engine thrust settings. Engine thrust is determined by inserting the related (assumed) temperature in accordance with prior performance analysis, in order to save the engine from harm caused by excessive high temperatures. Still, other methods can be combined to reduce take-off thrust settings such as "de-rated" take-off or climb.

Finally, the take-off speeds programming should be concluded by inserting flap position for take-off and CG (the airplane's center of gravity) trim into the FMC, based on information from the data card or directly from the laptop. The FMC requires that aircrew validate V1-, Vr-, and V2-FMC-generated speeds in the appropriate fields of the FMC (depending on the FMC version, pilots should insert speed values, rather than validate them). By validating or inserting these V-speeds on the FMC, reference marks of these speeds are then displayed on the cockpit's airspeed indicators. In airplanes with analogical or hybrid (analogical/digital) displays, pilots may have to adjust the speed bugs (reference markers on the airspeed indicators).

The validation of the FMC's V-speeds is also (depending on the airline) performed by cross-checking the V2 speed generated, with the GW V2 chart, which is usually a plastic card with a table of GW and related V2 values.

4.4 Checklist readings

After the FMC programming, the aircrew will perform departure checklist readings, in order to establish a common ground for the operational actions during the take-off and initial climb. When doing this, the crew should cross-check weight and speed parameters for take-off, according to the available data in the cockpit. These data are now supported by multiple (technical) artifacts, such as the load sheet, data card, laptop, FMC, and the cockpit's speed indicators.

The above outlined determination of the typical course of actions for the calculation of take-off speeds (with and without cockpit computers) shows that (a) the process involves entering a set of values in the cockpit (weights and performance parameters), processing of these values, and ends with specific marks on the cockpit's speed indicators; (b) the process uses preliminary and final information about estimated operating weights, in order to conduct the calculation; (c) the process requires cooperation of several agents (computers, pilots, and ground staff—flight dispatchers, loading- and fueling agents); and (d) the process connects people and artifacts following an algorithmic logic of procedure (e.g. firstly, entering values on a runway analysis chart; secondly, computing operational parameters; thirdly, transcribing this parameters onto the data card; and fourthly, inserting these values into the FMC).

5 Delimitation of the joint cognitive system under analysis

The cockpit is the place where the calculation of the take-off speeds occurs. Several agents and artifacts interact in order to produce these take-off speeds (Fig. 1). These interactions involve the performance of many sub-tasks, distributed across the agents.

Agents are single players, human or machine, able to execute actions based on different inputs. The main human players in the cockpit are the pilots (captain and first officer). In some situations, there may be extra aircrew members, such as the flight engineer (required in some types of airplane), or a third pilot. Air traffic controllers, company staff, or minor agents, such as fueling and loading people, were considered elements of the environment, not of the joint cognitive system under study, because they cannot control the cockpit calculation, despite their influence on the outcome of the calculation.

The main machine players in the cockpit are the laptop and the FMC. We consider them agents because these machines perform actions related to the cooperative functions in the system. These machines have cognitive capabilities (Cook 1996; Klein et al. 2004; Nemeth et al. 2004; Woods et al. 2009), such as control authority, information processing, and decision making. According to one of the pilots interviewed, "[the FMC] can be seen as another pilot inside the cabin. It is somebody else to share tasks with, but it is also somebody else who you will need to be monitoring and synchronize with during the operation." Moreover, it is not unusual to hear pilots state things like "what is he doing?" when programming or monitoring automation. Note in this sentence that automation is described as another subject ("he") performing actions. This latter example also reveals clear evidence of a lack of coordination between the human and the machine agents.

Fig. 1 Cockpit as the joint cognitive system under analysis

In this sense, each set of goal-oriented interactions of people and artifacts (machines) related to the calculation of take-off speeds is part of the (joint) cognitive system and functions as the unit of analysis formed by the human–work–artifact relation. An example could be the captain calling out the operating weight values to the first officer by means of reading them from the load sheet. At the same time, the first officer is entering these numbers into the laptop. Three cognitive systems are interacting in this situation: (a) the captain reading the load sheet values; (b) the first officer entering these values into the laptop; and (c) the information transfer of symbolic values between pilots.

Each of these cognitive systems is driven by internal representations that create a shared representation of the "joint" (cockpit) system. As a result, the cockpit performance of take-off speeds calculation depends on both the performance of single individual cognitive systems, as well as the joint cognitive systems' interactions. For this reason, we take the cockpit, the joint cognitive system (not the individual human or machine agents), as the unit of analysis.

6 Analysis of the performance of properties of the joint cognitive system (the cockpit) and their possible vulnerabilities

6.1 The cockpit representation

Representations are external and internal transformations that occur between people and artifacts. People's internal representations are based on temporary constructions and re-constructions of salient aspects of the situation, so defined in accordance with the Neisser's (1976) concept of schemata. Nevertheless, Hutchins (1995b) provided a consistent description of how artifacts can also be seen as external representations of the natural world.

For example, during the definition of the take-off operating weights, external representations provided by several artifacts in the cockpit (e.g. the load sheet, the flight plan) constitute the pilots' representation of the working situation. This constitution produces local cognitive system representations; at the level of the captain, when reading the load sheet; at the level of the aircrew, when the captain is calling out weight values to the first officer; and at the level of the first officer, when he hears the captain call out the weights. At these levels, internal (the pilots' minds) and external (e.g. entering weight values into the laptop) transformations are temporary forming the representations. Unique, but partial (always incomplete), the cockpit representation is created like a joint system's representation.

The load sheets used by airlines to inform the aircrew about the ZFW sometimes have weight data presented in different units, such as kilograms and thousands of kilograms. Taking into account a load sheet with the ZFW registered in units of kilograms, for example "ZFW = 42,500 kg", and given that the FMC registers the ZFW in thousands of kilograms, "ZFW 42.5", it is possible to imagine that the following three representations of the same operating parameters are likely to happen: (a) load sheet, "ZFW equals 42,500 kg"; (b) pilot, "ZFW equals 42,500 kg"; and (c) FMC entered value, "ZFW 42.5" (in the appropriated field). As a result of these various temporal constructions and re-constructions by these multiple agents, a possibly confusing cockpit representation of the actual ZFW is created in the joint cognitive system.

According to Loukopoulos et al. 2009, ephemeral representations are susceptible to interferences of the pilots' prospective memory. Prospective memory is the self-initiated (not directly based on external stimuli) remembering, in order to perform an intended action. Some of the incidents that were analyzed involved situations where operating weight parameters where not updated. In one specific case, the pilots decided to re-fuel some extra kilos and, during simultaneous tasks performance, they forgot to update the new TFW value in their computations, leading to distortions in GW determination and consequently the V-speeds production (Transportation Safety Board of Canada 2006b).

Verbal communications are among the most common ephemeral representations. For example, the verbalization of the ground staff of preliminary values of operating weights (Prelm.ZFW), communications with re-fueling agents, and minor load agents, as well as radio-communication with air traffic services. These ephemeral representations occur between pilots, mostly when one is calling out operating values to another or when they are performing checklists. They are susceptible to various constraints of the working phase, such as multitasking management, interruptions, lack of sequence and orderliness, and the use of estimated versus actual values.

In sharp contrast with ephemeral representations, some artifacts produce strong and durable representations constituting the cockpit's temporary representation, such as the data card or the default values of the laptop. In one of the analyzed incidents, the data card values from the take-off of the previous flight were mistakenly used to carry out the calculation of operating take-off parameters (National Transportation Safety Board 2001). In another incident, the laptop default value of take-off GW from the previous flight was used (Transportation Safety Board of Canada 2003).

Another computational problem happens when the joint cognitive system, the cockpit, mismatches the first digit of the GW for an immediate lower level. In one recent case, a GW of 347,000 lb was computed as 247,000 lb (Australian Transport Safety Bureau 2009). Once such (possibly incorrect) values are validated on the take-off data card during the ephemeral processes of transcriptions from one media to another, and inserted in the computers, the entire system is provided with this new representation. Double-checking of the procedures that leads to V-speeds will probably not reveal the inaccuracy of these values and the consequent representations.

Failures in this process are mostly related to the creation of meaning. If the meaning is something considered plausible for the situation, the representation will be easily accepted as valid. For example, a GW above the maximum take-off structural weight should be refused as valid meaning by both, the computer and the crew. On the other hand, values floating between the maximum and empty weight are possible to be considered and accepted across different medias in the cockpit. Studies have showed that pilots, especially when transitioning from one type of aircraft to another (e.g. from Airbus A330 to Boeing B747), are not able to identify orders of magnitude values related to weight or speeds, due to its constant fluctuation during natural operating contexts (LAA 2008).

In three recent incidents, the ground staff provided the aircrew with incorrect operating weight values of either ZFW or GW (Accident Investigation Board Norway 2004; Aviation Safety Reporting System 2009a, b). The weight values upon which the V-speeds are calculated are virtual, because there is no possibility for the cockpit (pilots or computers) to check the received values, as there is no system available to actually weigh the airplane. In this way, the received weight values are just "virtual" values that create a cockpit representation of a presumed airplane weight. Additionally, the actual values of ZFW, TFW, and GW are always changing, because during the calculations, the airplane is being re-fueled and loaded. As a consequence, both, the preliminary and the final values are responsible for the construction of the cockpit's weight representation.

6.2 Interactions in the cockpit

Three general types of interactions occur in the cockpit during the calculation of take-off speeds: (a) interactions between artifacts; (b) interactions between pilots and artifacts; and (c) interactions between pilots.

6.2.1 Interactions between artifacts

Interactions between artifacts involve situations in which artifacts are transforming representations and executing actions. In some airlines and aircraft types, the ACARS sends information about ZFW, TFW, and GW to the FMC. The FMC then generates V-speed values and sends these to the cockpit's airspeed indicators. All data are communicated from one artifact to another by means of a digital binary language and processed according to specific algorithmic protocols. The basic design assumptions behind the interaction of the artifacts are to relief the pilots' workload and amplify their capabilities to perform parallel tasks by means of automating these duties. In doing so, humans are kept away from this part of the cockpit's construction of representations.

6.2.2 *Interactions between pilots and artifacts*

Interactions between pilots and artifacts attempt to amplify human capability to perform work (e.g. physical, sensory, or cognitive amplification) (for further discussions about amplification of human capabilities, see Hollnagel and Woods 2005). There are two types of interactions when humans are using artifacts to carry out work: (a) embodiment-based interactions and (b) interpretation-based interactions.

In some tasks, certain artifacts are embodied by humans, whereas others are not. For example, a pen is a typical artifact designed to amplify human capability to write. It is embodied in the human part of the cognitive system "human-writing-pen." A person uses the pen as an extension of his or her fingers when he or she is writing. The nature of this interaction is the so-called co-agency, as the activity is equally produced by both the human and the artifact (Hollnagel and Woods 2005). Some tasks in the cockpit are embodiment-based interactions, such as handling the stick and rudder to control the airplane. In doing so, skilled pilots fly the airplane as if it is an extension of their own body and functions, such as a bicyclist cycling on his bike in a very skilled manner, or even a police officer wearing his uniform.

On the other hand, interpretation-based interactions occur when one person is using a non-embodied artifact, requiring higher levels of cognitive activity, interpretation, and commands. In this sense, the tasks related to the take-off speeds calculation are more interpretation-based interactions. Pilots should interpret both, numbers on paper documents (e.g. flight plan, load sheet, runway analysis charts, sometimes with different magnitude of cognitive effort), as well as computer fields and operative status. In these cases, the interactions strongly depend on the way humans produce meaning about the working situation, when using these artifacts.

Fennell et al. (2006) examined FMC tasks and errors of 22 pilots who only recently qualified for operating the FMC. Their results suggest that errors are most frequent when the task to be performed and the FMC function do not directly match, therefore demanding pilots' mental interpretation and reformulation of the task to access the proper FMC function. The same goes for the computations of the take-off parameters (previously described) with or without a laptop.

When using runway analysis charts (calculations without a laptop), a sequence of symbol manipulations is performed. Firstly, the proper airport, runway, and flap chart should be selected (some incidents involved the use of the incorrect chart). Secondly, the current value of outside air temperature should be found on the chart in order to identify corresponding values of GW related to performance implications about field and climb weight limits (some incidents involved errors in using the data chart correctly). Then, the new limitation value for the GW should be compared to the previous load sheet value, and if lower, another operation of the chart should be performed. Similarly, a transposition of the GW value should be done onto the correspondent GW column and respective values of outside air temperature, thrust limit, and V-speeds should then be registered on the take-off data card (common errors involve failures of the determination of the values and on its transcriptions to other medias). Still, a series of performance adjustments (e.g. whether air-conditioning packs are on or off, or whether runway surface is dry or wet) should be conducted in order to adequately set GW, V-speeds and take-off engines thrust.

On the other hand, when a computer is introduced in the process of performing these calculations, the demands on the system's representations are reduced. If a laptop is used, the pilot should initialize the proper software, select the engine thrust configuration, and the performance page. Then, a series of inputs related to departure runway, temperature, runway conditions, wind, aircraft anti-ice, aircraft bleeds and air-conditioning packs and optimum flap should be inserted in the computer using drop-down menus. After entering these values, the pilot commands to "calculate" values of GW, V-speeds, flaps position, and engines thrust setting. If the new GW calculated by the laptop is less than the planned GW, the pilot should return to the laptop software and re-calculate take-off performance using maximum thrust values (since the reduced thrust values are usually the default values of the software). There was one incident where the default value was mistakenly used (see Transportation Safety Board of Canada 2003). In such a case, the pilot should enter the actual GW in the planned weight block and carry out the calculations again. The new take-off performance values processed and delivered by the laptop should then be transcribed onto the take-off data card or directly into the FMC.

Six of the eighteen incidents analyzed for this paper involved situations of failures of entering values into the incorrect field of the FMC, mostly the unintended entry of ZFW in the GW field (Accident Investigation Board Denmark 1999; Aviation Safety Reporting System 2009c;

BEA 2006, 2008; National Transportation Safety Board 1999; South Africa Civil Aviation Authority 2003). According to the National Transportation Safety Board (2005), a number of bulletins have focused on FMC design improvements. As a result, more recent generations of the FMC do not permit insertions in the GW field. The FMC automatically calculates it by adding inserted values of ZFW and TFW. The computer also has provisions to flag GW or ZFW values that are less than a minimum value and will also flag input weight values greater than the maximum structural take-off gross weight. However, it still has no possibility of checking the validity of input weight values that fall between these minimum and maximum values. In one case, the FMC indicated a landing weight that was less than both the ZFW and operating empty weight, which the system and the flight crew did not recognize (National Transportation Safety Board 2001).

Five of the incidents analyzed involved situations of errors in inputting (typing) information into the computers (Australian Transportation Safety Bureau 2009; Aviation Safety Reporting System 2009d; BEA 2007; Transportation Safety Board of Canada 2006a, b). Some possible solutions have been proposed to address these problems (National Transportation Safety Board 2005), such as: (a) uplink the GW informed by flight dispatchers from the ACARS, instead of having the crew type it into the computer; (b) inhibit any entry in the GW field, which would eliminate the possibility of flight crew erroneous entering ZFW in the GW field; (c) prevent entry of airplane weights that would result in landing weights below ZFW or values of operating weight.

The FMC also allows V-speeds to be changed into values significantly lower than those it had derived, even when the GW has not been changed correspondently. In this sense, it is not designed to detect and annunciate incorrect entries. In one case, despite the erroneous ZFW and GW values entered into the FMC, the flight crew accomplished the take-off using reference speeds related to the airplane's actual weight. The investigation showed that the crew most likely modified the FMC-derived reference speeds for take-off (National Transportation Safety Board 1999).

The use of a laptop, instead of runway analysis charts, reconfigures the flow of representations in the sense that different, but relevant, steps for speeds calculation are performed. Also, the values define a different kind of interaction between the agents in the system, since the laptop is included in the coordination process as a new agent. The computer, as a new system agent, starts to share the systems' representation at the moment the pilot introduces performance values using drop-down menus. In doing so, another agent is incorporated in the network responsible for the system's performance. In a different manner, instead of manipulating information on a higher level of abstraction to perform the calculations, the pilot leaves this action to the machine and just waits for results (but is that another parallel process of computation that needs to be managed).

6.2.3 *Interactions between pilots*

There are multitude of interactions ongoing when the V-speeds values are produced in the cockpit, especially because the activity of V-speeds calculation is always carried out during the preflight preparation. Therefore, it is only one of the multiple tasks performed by the crew at that time (Loukopoulos et al. 2009, discussed multitask and interactions during preflight).

Interactions between pilots in the cockpit have been studied in the field of human factors for over 30 years. Initially developed in aviation and later disseminated in other domains, Crew Resource Management (CRM) incorporates several dimensions of analysis of those interactions, such as Leadership, Communication, Situation Awareness, and Decision Making (Baker and Dismukes 2002; Flin and Martin 2001; Goldsmith and Johnson 2002; Helmreich et al. 1999; Salas et al. 2006; Thomas 2004). However, there is no general or clear definition of what good CRM is (Dekker 2000).

CRM can be criticized for focusing on elements of human behavior in detriment of the analysis of the cognitive system. In this sense, a joint cognitive system (JCS) approach to analyze the interactions between pilots in the cockpit, which incorporates the question of how the use of artifacts shapes those interactions, requires a cognitive analysis of coordination (see next section). Coordination can be seen as the orderliness of actions carried out in the JCS. It also considers how those actions produce resonance and activates other functions in the system (Henriqson and Saurin 2009; Woods and Hollnagel 2006).

6.3 The need for coordination

Klein et al. (2004) suggest four requirements for effective coordination, taking into account the cognitive dimensions of the situated activity: (a) interpredictability; (b) common ground; (c) directability; and (d) choreography.

Interpredictability refers to the agents' capacities to estimate features of other agents in the situation. Being team players, each member of the joint activity needs the ability to predict the action of the other players. Interpredictability at the level of interactions between pilots depends both on how pilots can take the perspective of each other during the activity and on how standard procedures are accomplished, including the division of the labor. For example, when the first officer delivers the operating weight values to the captain by calling them out from the take-off data card, he is also signaling the end of the computation of the take-off parameters to the captain. For the captain, this means that the generated operating values are ready to be entered into the FMC.

Interpredictability at the level of interactions between pilots and computers involves, at the same time, each part's capacity to estimate features of the situation of the other part. When the operating take-off parameters are being calculated by using laptops, pilots predict computer performance according to its algorithmic logics. Rather than being a task-driven calculation, its activity is mostly driven by the pre-defined programming sequence of steps that should be carried out. Sarter and Woods (1992, 1994) emphasized that the obscure interface between the pilots and the automation makes it difficult for pilots to track the state and the activity of the automation.

Poor interpredictability occurs in the cockpit due to the use of several virtual values (e.g. Prel.ZFW and Final.ZFW) and transitory representations (e.g. transcriptions of weight values from the load sheet into the laptop, from the laptop onto the data card, from the data card into the FMC) of operating parameters. At the same time, nuances related to the forms of presentation of weight values (e.g. different units, such as kilograms and thousand of kilograms) and several orders of magnitudes for GW and V-speeds influence the agent's capacity to estimate features of the situation of other agents.

Common ground is related to the shared representations that agents create from the information flow across the cockpit. During their work in the cockpit, pilots create a shared meaning (always partial and thus incomplete) of the working situation. Their representations are constantly calibrated and updated by means of communication forms, such as verbalizations, gesticulations, and manifestations of intentions during actions. These types of communication are ephemeral in the way that they are not sustained over time. On the other hand, artifacts in the cockpit may provide much stronger and more durable representations, such as data cards, which retain durable information about calculated take-off parameters.

According to Klein et al. (2005), sustaining a common ground requires various clarifications or reminders in order to be sure of something and to give team members a chance to challenge such assumptions. In one of the incidents analyzed, the pilots used the previous flight's take-off data card to program the FMC. When the take-off data are inserted in the FMC, the whole cockpit shares a common representation of performance values and further predictable actions during the take-off (e.g. when the pilot flying should rotate the airplane and what the initial climbing speed is, etc.).

Directability refers to deliberate attempts of an agent to modify the actions of another agent by means of giving directions. Although directability is mostly concerned with leadership and followership in the social dimension, it can also be seen as a property of some artifacts. For example, the FMC provides inputs to the fight director bars (on the cockpit's primary flight displays) related to the initial climb speeds based on the take-off calculations.

Poor directability can be sustained by the division of the labor (e.g. when each pilot is responsible for carrying out a specific set of actions during the flight deck preparation) or the lack of challenging the operating parameters entered into the FMC. The division of the work and the natural constraints of the working situation, such as multitasking demands and poor interpredictability, affect agents' capacity to synchronize. For example, an ergonomic inspection of three FMCs realized by the Laboratoire d' Anthropoligie Appliqueé (LAA 2008) revealed that none of the three types of FMCs displayed the status of the operating weight, in prompting that these values were forecasted or final. Additionally, items related to the thrust settings on the respective page of the FMC (such as TO1 and TO2) are not part of the load sheet information. The information that must be entered or checked is not displayed on the same screen.

Choreography involves synchronization of the entry and exit points of the joint activity requiring signaling tips. Signaling has implications for cockpit coordination because of its importance for synchronization, communication, redirection, and diagnosis. Agents need to clearly announce their current intent and enable other agents to anticipate the consequences of their actions. Each action of the take-off speeds calculation is, at the same time, an exit of the current action and an entry point for the next action in the cockpit. Although human choreography is not always linear and sequential, due to the multitasking demands of the activity and the use of preliminary and final parameters (e.g. Prelim.ZFW and Final.ZFW), the logic of interaction with computers demands linearity and synchronization according to algorithmic logic.

Choreography is not just a matter of task standardization or a production of a good "screenplay" for the agents. Nor is it just a matter of motivational attitudes or behavioral skills, such as leadership. Evidence points out that coordination is a matter of joint control capacity, based on feedback and feedforward mechanisms. During observations of flight simulation, failures of coordination, such as the lack of synchronization and interpredictability, resulted in the loss of some degree of control.

6.4 Control of the V-speeds calculation by the cockpit

Even though some researchers have claimed that the concept of control is central to the analysis of JCS performance (Hollnagel 1998, 1999, 2003; Hollnagel and Woods 2005), we still need a precise definition of what control is. According to cybernetics, control is a process involving a sequence of behaviors that lead a system toward its goals (Woljter 2009). Cognitive systems theory has adopted a cybernetics approach to define control by its circularities of feedback and feedforward. This approach combines, the cybernetic notion of regulation (Ashby 1959; Woljter 2009), the Perceptual Cycle of Neisser (1976) and Hutchins' ideas of distributed cognition (1995a, b), to provide a functionalist approach of control. In this sense, control 'happens' during the interaction of "human–task–artifact" and is goal oriented and influenced by the context in which the situated activity happens.

The system's feedback and feedforward loops are essential functions of control circularities (Hollnagel 2002). The first refers to information provided by salient aspects of the situation, while the second represents anticipations of the current situation. Feedback and feedforward determine the way representations are produced and, consequently, the way actions are selected and events are fashioned. Three main circularities of dynamic control can be identified during cockpit calculations, as defined in the scope of the afore-discussed three cognitive systems: (a) circularities of control based on captain–task–artifacts interactions; (b) circularities of control based on first officer–task–artifacts interactions; and (c) circularities of control based on pilots–teamwork–artifacts interactions.

The control of the V-speeds calculation is rather a multitasking management process than a linear single process. The calculation activity involves a set of tasks performed in the cockpit during ongoing flight deck preparations. Inputs, resources, and outputs of this activity are interrelated and produce resonances in other activities. For example, the definition of the take-off operating weights is the input for the take-off speeds computations, involving resources (such as, data from the load sheet, airport service, ground staff, and flight plan) and consuming time and costs of coordination among pilots and computers. The output is the generated operating speeds to be inserted in the FMC. Most of the inputs are feedback based but feedforward is required when using preliminary values. The way these data are reconciled produces temporary representations at the level of the cockpit, which enable plausible options for the choice of the next action.

This means that the control circularity process is neither linear nor causal. It challenges the situation awareness theory and Information Processing System (IPS) models of human cognition and decision making (see Endsley and Garland 2000; Wickens and Hollnads 2000), by saying that feedback and feedforward actually coexists. It is not the result of a linear process of signal detection, perception, comprehension, and decision, which then results in an action as the output. Every feedback has components of feedforward, because it is a just-in-time consequence of meaning creation at different levels (e.g. pilots, cockpit).

It is reasonable to consider that, if the representation at the level of the cockpit is always partial and incomplete, failures are perceived as outcomes of controlled situations, not of uncontrolled activity (as it is reasonable to imagine that the cockpit would not take-off without the calculated V-speeds). This means that the V-speeds' outcomes are always a process that is vulnerable to regulation activities inside the cockpit. Consequently, it seems to make sense to consider that a mismatch in cockpit calculation is rather a controlled process involving constant meaning creation by the system, with actions deliberated chosen toward goals, than failures in selecting proper actions due to the lack of operators competence, lack of situation awareness, or complacency.

One way in which flight crews often cross-check data card values is through validation of each step of the procedure. In this case, the captain will check on the laptop all of the values inserted by the first officer, following the same steps used to perform the original take-off calculations. The final data card can be considered as an outcome of the process of meaning creation that activates a cockpit representation of take-off performance. This process of meaning creation involves a series of steps and information processing between different cognitive aids, technical and social artifacts, where a reasonable outcome for the agents emerges and reinforces plan continuation. Checking this outcome is rather the validation of the steps of the process of meaning creation than checking the explicit result of the outcome.

An analogy can be the mathematical validation of a simple product operation. For instance, if we type in a calculator "2" "×" "3" "equals" (=6) and we wish to check the accuracy of this calculation (or the outcome), we do this by following the same procedure "2" "×" "3" "equals" once more. We rather cross-check the operation that leads to the "6" than the validity of the "6" as the outcome, or the "2" and "3" as inputs. In this manner, when the captain is checking or typing the same values in the same order in the laptop or in the FMC, he is validating the process rather than the outcome, the GW or the take-off speeds produced. This is why double cross-checking or parallel calculations are not independent and thus not fully efficient.

Once the data card or laptop parameters are validated by the pilots, they become the most important references for the meaning creation of performance values in the cockpit. Once the cross-check of these values and the process to attribute meaning to them are confirmed, a strong and durable representation is materialized. This representation will probably not be challenged about its validity again.

7 Conclusions

Like Hutchins (1995a), we took the cockpit as the JCS under analysis and we put focus on the analysis of the joint tasks; i.e. the work. We tried to show that the system's performance is not uniquely a consequence of pilots' capacity or even the computers' design, but that the interactions between people and artifacts create cognitive systems. The recent JCS concepts that put focus on performance analysis reveal (dis)joint interactions and how these interactions activate plausible course of actions in the system.

In order to delimitate the cockpit as the JCS under analysis, we established a set of criteria based on a review of the literature about Cognitive Systems Engineering and adapted this in a pragmatic way to the analysis of the calculation of the V-speeds. These criteria considered the definition of each set of goal-oriented interactions mediated by agents and artifacts, and its capacity to intervene in the control of the calculation of the take-off speeds. Alike the pilots, the laptop and the FMC were defined as agents in the cockpit. This reflects a new perspective on team performance in cockpits, more dependent on the employed cognitive activity than on pilots' attitudes.

The incidents and accidents that we analyzed were related to the following events: (a) failures in insert values onto Laptops, FMC, or ACARS; (b) failures in V-speeds check due to lack of orders of magnitudes' parameters or capturing it while performing checklist verifications; (c) failures in the registry of weight and speeds onto the take-off data card, laptop, FMC, or ACARS; (d) failures in the use of laptops; (e) use of previews fight data for the calculation of actual performance; (f) failures in the data manipulation during calculations using Weight and Speed charts; (g) failures in field selection of the laptop, FMC, or ACARS for the insertion of weight and speed values; (h) failure in the Weight and Speed Chart selection for the definition of the operating parameters; (i) failures in the remote definition of operating parameters; (j) failures in data calculation during the use of the Weight and Speed Charts for V-speeds production; and (k) failures in data conversion.

Given that the calculation of the take-off speeds is a highly procedural activity, it involves several cross-checkpoints and intensive use of technology. Why then are errors not detected? Why do these types of incidents happen? We used joint cognitive system concepts to discuss possible vulnerabilities that this activity is exposed to. In doing so, we identified four assumptions for its vulnerabilities: (1) representations at the level of the cockpit are always partial and incomplete; (2) some interactions require interpretation rather than embodiment relations; (3) interactions between agents do not follow a canonical process of coordination; (4) the control of the prevention of failures is accurate but inadequate.

Representations at the level of the cockpit are always partial and incomplete because: most of them are ephemera; machines process numbers, whereas humans produce meaning of the working situation given their knowledge, goals, and constraints; and because the operating parameters are virtual values.

The pilot–artifact interface is characterized by an interpretation-based interaction, rather than an embodiment-based interaction. The computation of operating parameters using laptops, the FMC, or runway charts involves different modes of interpretation-based interactions. The first two (using laptops or the FMC) are a co-agency process where pilots enter data in the laptop or the FMC and receive outcome values or events, which show fragilities regarding its cognitive distributed nature. The latter involves pilots' heuristics to select the proper chart and manipulate symbols on those charts, which demands higher cognitive efforts and again pilots' heuristics to perform the task.

The flight deck preparation phase—when the take-off speeds are calculated—does not follow an established procedure. When pilots are setting-up the cockpit for take-off, they have to deal with the contingencies of the natural work related to time pressure, multitasking demands, interruptions, and partial and incomplete representations. The take-off speeds calculation has to take into account several variables that are not easily and accurately foreseen.

Considering the constraints of the natural work, it is easy to see that the calculation of the take-off speeds requires simultaneous and multiple levels of control. In the same way, coordination requirements are partially considered. The requirements for multiple and simultaneous levels of control, as well as the incidents involving incorrect data conversion, the failures in weight and speeds representation, and the inadequate updating of preliminary parameters, illustrate how coordination is currently rather a brittle than a resilient process.

Corroborating the findings of an extensive study about the use of incorrect parameters for take-off, conducted by the LAA (2008), we argue that the events involving take-off speeds calculations are not only related to errors in the input of weights into the FMC, but rather to the entire process of the computation of take-off operating parameters (i.e. failures in manipulation of symbols), as well as to the entering (i.e. use of unchallenged and virtual symbols) of these computed values into the FMC. The ineffectiveness of the control to detect these failures is often carried out by item comparison and replication of the procedure. However, "one wrong item" times "another (wrong) item" = "wrong outcome" is an accurate but inadequate form of failure avoidance.

Different initiatives have been deployed in the industry to provide safety redundancies in order to contain events involving undesirable actions (human errors) and consequences (accidents/incidents). One of these is the creation of new procedures, which are allegedly safer, with more cross-check and double cross-checks. Another is the adjustments of hard- and software; aircraft manufacturers are providing more constricted boundaries of their artifacts in order to support pilots' work.

In answering the aviation authority's question about accidents and incidents involving take-off speeds calculation, a major manufacturer stated that the establishment of reliable procedures for verification of manual operations as well as the thorough check by another properly trained person should reduce the likelihood that these events would occur by several orders of magnitude. They also recommended that operator training and procedures must be established to ensure that this verification is accomplished consistently and carefully. Following the aviation authorities' recommendation to implement safety barriers on the FMC programming of take-off speeds, several enterprises have been addressing the FMC software logics (such as ZFW and V-speeds cross-check parameters).

Most of these initiatives produce a triple paradox in the creation of safety. The more double-checking and cognitive redundancy among artifacts and people in the JCS, the more "entry points" we create for unexpected cognitive dysfunctions that can amplify chances of unsuccessful performance. Thus, improving joint cognitive redundancy in the system may help create the idea that the process is extra safe and invulnerable. Still, we tend to consider the human as the most fragile part of the system. However, by installing this type of redundancy, we expect the humans in the system to perform more actions, thereby taking more time and consequently reducing the amount of cognitive resources available to support the flow of representations through the cognitive architecture.

CSE researchers have argued that design requirements for machines should take into account the cognitive image of the operator (e.g. Hollnagel 1998; Woods 2003). However, in doing so, CSE researches are focusing on a "cognitive image" developed by researchers of the first cognitive revolution, inspired by the information-processing paradigm. As a result, this "cognitive image" is ironically rather an image of a machine than that of human cognition. The idea of cognition as a distributed phenomenon, with the joint cognitive system as unit of analysis, allows a promising way to understand vulnerabilities in specific high-technological working situations. In this paper, we argued that the analysis of cognition must focus on the performed activities, and that in this manner, humans and artifacts need to share a cognitive image of the task.

In this sense, this paper proposed a different view on failures in complex socio-technical systems. Instead of focusing on the investigation into human performance and design of related technology, the investigation into failures will gain a lot from a human factors perspective based on cognition and interactions as situated and distributed phenomena.

The interviews were used as a manner to identify pilot's approach to the calculations of the V-speeds and to discuss preliminary findings from the preceding documental analysis and observations. Most of their comments were very behavioral oriented and were then excluded, because the perspective of CSE is not about how pilots should follow the SOPs, or how they should try harder to avoid human errors. In contrast with CSE, pilots usually agree with accident investigators and believe that the performance of the activity is fully dependent on their capacities.

As a final remark, we would like to suggest some ideas for future designs by focusing on the analysis of the interactions between humans, work, and technology. Designers should provide the cockpit with better means of representation of the operating parameters, taking to account that a joint system representation should created, rather than only humans' representation. Interactions between artifacts and humans should be designed from an ecological perspective, which valorizes embodiment relations, rather than interpretation-based interactions. Support for coordination should be analyzed as a way to amplify the capacity of cognitive systems to maximize performance, by means of support for common ground, interpredictability, directability, and choreography.

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