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Studying decision processes via a knowledge management lens: The Columbia space shuttle case ☆

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ABSTRACT

While the role of knowledge management (KM) for decision support is well acknowledged, there is a gap between existing KM theory and actual KM practice in real-life decision-making. This paper aims to illustrate this gap by studying the report of the Columbia Accident Investigation Board, focusing on diagnosed pre-explosion problems in decision-making processes, and prescribed post-explosion recommendations. The paper's research contribution is two-fold: 1) consolidating two KM frameworks to one research tool, to serve as lens for studying decision-making processes and 2) providing convincing evidence regarding the role of the KM perspective in organizational decision-making processes.

1. Introduction

Following the Columbia shuttle accident on February 1, 2003, the Columbia Accident Investigation Board (CAIB) issued a report [10] that linked decisions made at NASA with the accident[1]:

> "This decision made by the Program Requirements Control Board at the STS-113 Flight Readiness Review is among those most directly linked to the STS-107 accident. Had the foam loss during STS-112 been classified as a more serious threat, managers might have responded differently when they heard about the foam strike on STS-107. Alternately, in the face of the increased risk, STS-107 might not have flown at all. However, at STS-113's Flight Readiness Review, managers formally accepted a flight rationale that stated it was safe to fly with foam losses. This decision enabled, and perhaps even encouraged, Mission Management Team members to use similar reasoning when evaluating whether the foam strike on STS-107 posed a safety-of-flight issue." (Page 125).

The CAIB report acknowledges that Knowledge Management (KM) practices and processes are of relevance to and may impact decision-making. Yet, it interprets the events through insights gained from both the contemporary social-science literature and the expertise of experts in the fields of Normal Accidents, High Reliability and Organizational Theory (Page 180). In addition, without addressing the KM perspective, the CAIB report refers to a previous NASA report which acknowledged bad decision-making processes in the context of the Challenger accident (Page 99).

The interrelation and interaction between KM processes and decision-making processes is well recognized. In fact, effective KM is considered a must for decision-making in general [4,19,24], and within the space industry in particular [11,22]. Moreover, Leidner and Kayworth [15] argue that Knowledge Management Systems (KMS) can support such processes as staff reducing, business dynamics, decision-making and problem identification, as did Management Information Systems (MIS), Executive Information Systems (EIS) and Decision Support Systems (DSS) in the past. KM can also affect strategic decision-making in the sense that decision makers can learn from decentralized strategic decisions made by autonomous managers, allowing the organization to be more responsive to a volatile environment [19]. Moreover, KM can contribute to decision-making not only by sharing past experiences, but also by providing knowledge resources [12] and decision-making structures based on knowledge inside and outside the problem domain [24]. KM may also empower decision makers who face time pressures, risks, contradictions and information overflow, under mission-critical decision scenarios involving prevention, event recognition, early and sustained response, recovery and the like [24]. In addition, KM is valuable for determining

☆ This paper is dedicated to the memory of the seven astronauts who were killed in the Columbia crash, including Israel's first astronaut Colonel Ilan Ramon, as well as to the memory of his son Captain Asaf Ramon, whose Israel Air Force plane crashed a few months after graduating from pilot school and from the authors' university.

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[1] All the quotations in this paper are cited from Parts 2 or 3 of the CAIB report — Volume 1 [10].

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which information is needed for decision-making and for overseeing the acquisition and dissemination of information [33].

Courtney [5] incorporates KM components into a new DSS paradigm to allow organizations address complex decision-making situations in global, volatile and dynamic environments, encompassing technological, organizational, social, individual and ethical perspectives, thus requiring unbounded system thinking that KM can provide. Several theoretical KM frameworks, which interact with organizational decision processes, have been developed as well [4,19,24,30,33]. Yet, according to Garrett [9] there exists a gap between these theoretical KM models and their practical implementation in real-life decision-making. In his study of the Challenger and Columbia accidents from a knowledge-analytic perspective, he has focused on the differentiation between top-level managers' knowledge and mid-level managers' knowledge. Realizing the bounded rationality and the limited cognitive capabilities of decision makers [1,13,16,26,29] and extending Garrett's knowledge-analytic perspective, the two main objectives of the thorough content analysis of the CAIB report conducted in this work are: 1) to find which of the pre-explosion problems in NASA's decision-making processes, as diagnosed in the CAIB report, are related to KM, and 2) to determine whether the post-explosion recommendations, as prescribed in the CAIB report, not only provide evidence that KM practices might have made a difference but also fully address all KM-related problems.

Section 2 briefly reviews past KM research and practice. Section 3 describes the two phases of the research method employed in this study. In the first phase, a KM research tool is developed by consolidating two existing KM frameworks (denoted hereinafter Framework A and B) into one. In the second phase, the developed tool is applied as a lens for content analysis of the CAIB report. These two methodological phases lead respectively to presentation of the results in Section 4, devoted to developing the KM analysis lens (denoted hereinafter Framework C), and Section 5, devoted to studying the Columbia shuttle case by conducting content analysis of the CAIB report via the lens of Framework C. The data for the analysis in Section 5 includes both the pre-explosion problems in decision-making processes before and during the Columbia shuttle flight, as diagnosed in the CAIB report, and the post-explosion recommendations for future improvements, as prescribed in the CAIB report. Section 6 discusses the paper's limitations and two research contributions: 1) consolidating two KM frameworks to one research tool, to serve as lens for studying decision-making processes. One of the frameworks is focused on crisis situation, providing means for global knowledge distribution and encompassing knowledge activities throughout the whole knowledge lifecycle. The second framework is more general, with emphasis on managing decisions and decisions rationalism knowledge. The consolidated framework aggregates the perspectives of both frameworks, and thus is more robust than each alone and offers a more comprehensive analysis. 2) Providing convincing evidence regarding the role of the KM perspective in organizational decision support. Finally, in Section 7 we conclude with emphasis of the KM role in support of organizational decision-making processes, using the CAIB report to illustrate the existing gap between KM theory and practice in real-life decision-making, and on what can be done to narrow it. We also provide recommendations for future research and practice.

2. Knowledge management: background

According to Stenmark [28], knowledge is considered tacit while information and data are explicit and tangible. Davenport and Prusak [6] elaborate on how information becomes knowledge by activities of making comparisons, thinking of consequences, making connections and sharing opinions in conversations. Knowledge practices involve reasoning about information and data while leveraging performance, problem-solving, decision-making, learning and teaching capabilities [2].

Against this background, managing knowledge has become an important strategy for improving organizational competitiveness and performance [8,31]. KM frameworks for supporting knowledge management efforts can be classified as prescriptive, descriptive, or a combination of both [25]. A prescriptive KM framework provides a general idea on how to manage knowledge, while a descriptive one aims at specifying knowledge and procedures for a successful KM initiative. The KM frameworks that are discussed in this paper can be classified as combination of prescriptive and descriptive. Adding a systems-thinking perspective to the frameworks addresses the need for a cohesive KM framework which accommodates business strategies and goals [25]. Some KM frameworks [6,25] are general and some are oriented toward decision-making processes.

The framework ‘Distributed Knowledge Model’ (DKM), enhances DSS with a network of repositories, each of which is specialized in specific knowledge and knowledge contributors, facilitating knowledge exchange between decision makers [23]. DKM was examined in a health-care environment showing increases in efficiency, patient satisfaction and service quality. Another KM framework deals with project definition, an activity that occurs prior the design phase, which should be aligned with client and organizational knowledge [30]. This project-definition framework fosters a collaborative decision-making process which enables eliciting tacit knowledge towards establishing transparency of decision networks among various multi-discipline groups and stakeholders. A more specific KM framework deals with such KM strategies as personalization and socialization, as well as with tacit and explicit knowledge transformation, during the three intelligence, conception and selection phases of decision-making [19]. Also worth mentioning is a KM framework which emphasizes the importance of the business-process context for realizing KM efforts, where autonomous decision-making structures exist. Under this framework, decision processes are part of the operational core of knowledge, which includes also information processing, motivation structure and workflow execution, while KM efforts include knowledge storage and retrieval, knowledge sharing and knowledge synthesis [24]. Since a review of all existing KM frameworks is beyond the scope of this paper, we focus in this study on two decision-oriented KM frameworks [33,4] that are most comprehensive for decision support purposes in order to consolidate them into a research tool for this study as described in Sections 3 and 4.

3. Method

The purpose of the current research is to illustrate the importance of examining decision-making processes via a KM lens. To accomplish this aim, we chose to examine the NASA case study based on the report issued by NASA's investigating committee that inspected various data sources related to the Columbia flight, such as documents, emails and interviews with key stakeholders, and to study whether the pre-explosion problems in decision-making processes, as diagnosed in the CAIB report, and the post-explosion recommendations, as prescribed in the CAIB report, pertain to KM components relevant for support of organizational decision-making processes. The academic literature, in general, and the literature on decision support systems, in particular (e.g., [17,23]), has published robust research based on examining a single case study. Case study research allows the researcher to understand the nature and complexity of the processes, without a priori assumptions, and is appropriate if it represents a critical case for testing a well-formulated theory, or if it is an extreme and unique case [3,32]. The Columbia explosion is indeed extreme, unique, and critical for demonstrating the need to harness a comprehensive KM framework in decision-making. While our research conclusions are specific to the NASA case, the case research showed the critical role of KM in decision-making processes. This section briefly describes the research method used in this study to accomplish this objective, explaining how we developed the research tool, consolidating two existing KM frameworks (Section 3.1) and how we content-analyzed the CAIB report, via the lens of the developed research tool (Section 3.2).

3.1. KM framework development

The theoretical basis of the developed research tool is composed of two existing decision-oriented KM frameworks: Framework A deals with crisis situations where knowledge is distributed internally and externally [33] while Framework B embeds KM processes within decision support environments [4]. Development of the Framework C, to serve as the research tool in the study, involved three methodological phases (Section 4). First (Section 4.1), we visually described Framework A (Section 4.1.1) and Framework B (Section 4.1.2), with data flow diagrams, depicting every KM component of each of the two frameworks. Second (Section 4.1.3), we compared and contrasted both frameworks to identify every desirable KM attribute characteristic of each framework. Third (Section 4.2), to have the best of both frameworks, we consolidated them into Framework C while making sure that the KM components of Framework C enable the union of all desirable KM attributes featured by either Framework A and Framework B or both.

3.2. Content analysis of the CAIB report

Our study was based solely on the CAIB report which at the outset may seem like a single source of information. Yet, the report itself is based on more than 3,000 public input submissions (Page 235) and 75,000 documents with more than 450,000 pages (Page 235), related to the Columbia shuttle flight and the decision processes that occurred before and during this flight. In addition, the report is a work product of 13 members committee and not a single point of view. Therefore, it is actually representative of triangulation of data sources needed for validity and can serve as reliable source of information needed for establishing validity of the analysis. The analysis method used in this study is based on the qualitative grounded theory approach [27]. Grounded theory is appropriate for this research, focused on studying the decision-making processes from a KM perspective, since its objective is to enhance the understanding of social and cultural phenomena without formulating hypotheses in advance [7,14]. Content analysis of the CAIB report involved an inductive-analysis process [27] aimed at identifying KM-oriented practices which pertain to (a) problems in past decision-making processes, as diagnosed by the CAIB, and (b) recommendations for future improvements in decision-making processes, as prescribed by the CAIB. The segmentation process pursued via content analysis of the CAIB report included: segment identification, coding, and categorization. Segment identification involved reading the CAIB report to mark and enumerate segments (composed of one or more sentences) that describe either a diagnosed problem in past decision-making processes or a prescribed recommendation for future improvements in decision-making processes. Segment coding (i.e., open coding) involved associating the identified segments with codes that relate to decision-making and KM issues. Segment categorization (i.e., axial coding) involved either conceptualizing and transforming the open codes into a category with a corresponding matched attribute in Framework C (the research tool developed in Section 4) or, when no corresponding match could be found, into a newly defined emergent category. The thus revealed categories were iteratively refined until category stability was reached. Altogether, 198 segments were identified, coded and categorized (Section 5).

4. Developing a KM framework as a lens for analysis

The two parts of this Section describe how we developed the Framework C, which served as research tool used to yield the content-analysis results (presented later in Section 5): Section 4.1 compares and contrasts (Section 4.1.3) Frameworks A (Section 4.1.1) and B (Section 4.1.2), and Section 4.2 describes their consolidation to Framework C.

4.1. Frameworks A and B

4.1.1. Framework A

Zhang et al. [33] were motivated to present their KM framework in the context of humanitarian assistance and disaster relief, since many decisions taken in emergency situations are based on little knowledge other than that in the minds of the decision makers. Their framework deals with how to effectively gather relevant information in a timely and accurate manner, as well as with how to efficiently store, organize and manage knowledge to enable access, sharing and reuse.

A *Knowledge base* at the core of Framework A (Fig. 1) holds structured and unstructured information about disaster events, needs assessment, relief organizations, satellite images and geographic maps, along with past experiences and recommendations. The knowledge base is constructed by means of *knowledge activities* as knowledge acquisition, organization, creation, and sharing, to serve *decision makers* and various *stakeholders* during real-time *decision-making*. Designing the knowledge base includes specifying: what the critical knowledge is; who the knowledge contributors are; how the knowledge is to be structured, categorized and linked to other knowledge assets; how the knowledge activities are to be embedded within organizational processes; and which infrastructure is the most suitable for supporting the knowledge activities. Amplifying knowledge reuse is done by including in the knowledge base an ontology, which is a description of the objects, concepts, and relationships that exist in various areas of interest.

Framework A delivers the following desirable KM attributes:

- *Distributed* — Framework A enables decision-making by distributed groups, based on shared knowledge, and facilitates decision sharing and validating among different stakeholders distributed in the organization.
- *Knowledge base* — Framework A has a central and collaborative infrastructure, where knowledge can be organized for decision makers across the organization.
- K*nowledge lifecycle activities* — Framework A encompasses all knowledge-related activities (e.g., create, identify, collect, organize, share, adapt and use) that leverage knowledge usage and transfer [21].
- *DSS (Decision Support System)* — Framework A stands for an organizational system that facilitates decision-making.
- *CBR (Case-Based Reasoning)* — Framework A features a case-based repository of past cases and their solutions.
- *Recommendations* — Framework A has the capability to recommend a solution for a problem.
- *Internet infrastructure* — Framework A enhances the system usability by allowing remote access.

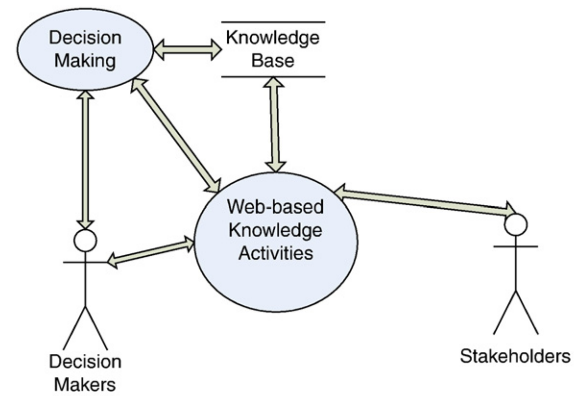

Fig. 1. KM components of Framework A [33].

- *Connection to people* — Framework A defines the stakeholders, both internal and external to the organization, as inherent part of the framework.
- *Security and billing* — Framework A acknowledges its relationships to the different stakeholders.

4.1.2. Framework B

Bollogu et al. [4] claim that decision-making processes and KM processes are interdependent and consist of activities that complement one another. In their KM framework, therefore, KM components, such as knowledge acquisition and distribution, are aimed at enabling and enhancing decision-making, whereas DSS components are aimed at supporting decision-making activities by providing means for acquisition and storage of decision makers' tacit and explicit knowledge.

The *DSS + KM* core of Framework B (Fig. 2) combines DSS and KM practices. Framework B's *knowledge base* is composed of two components. The first component consists of model repositories, relying mainly on database management, data warehousing, data mining and OLAP (On Line Analytical Processing). The second component incorporates Nonaka's [20] SECI model regarding Socialization, Externalization, Combination and Internalization human-based knowledge creation activities, thus reflecting the integration of DSS and KM aspects in the knowledge base. The externalization of decision models involves elicitation of problem-solving knowledge and decision-making argumentation from the *decision makers*; the combination of decision models can be achieved during their integration and generalization; the internalization of decision models corresponds to DSS building using elicited decision models; and the socialization of decision models is analogous to knowledge sharing by different decision makers (e.g., through group discussions), reflecting their tacit models. The processes of Framework B are based on machine-learning techniques which enhance decision-making effectiveness by fostering not only validation and verification of consistency in decision-making, but also alignment of decisions with organizational goals.

Framework B delivers four desirable KM attributes also featured by Framework A: knowledge base, DSS, CBR and Recommendations. Since Framework B focuses on decision models in accordance with Nonaka's model [20] of knowledge creation, it partially delivers the KM attribute fully featured by Framework A: knowledge lifecycle activities. In addition, three desirable KM attributes that Framework A does not feature are delivered by Framework B:

- *Generic* — Framework B is general purpose in the sense that it can serve decision-making processes in diverse organizations.
- *EIS (Enterprise Information Systems)* — Framework B interfaces between the KM and DSS components with an EIS.

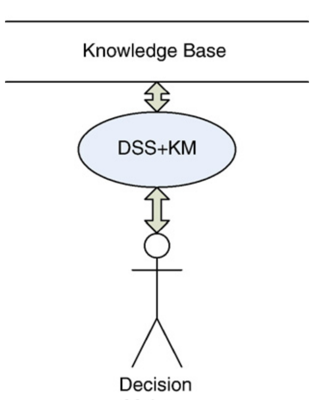

Fig. 2. KM components of Framework B [4].

- *Automated decision models collaboration* — Framework B refers to intelligent agents capable of analyzing the current problem and finding similar ones in the knowledge base.

4.1.3. Comparing Frameworks A and B

Frameworks A and B are compared and contrasted in Table 1 with regard to the desirable KM attributes. Framework A is oriented toward a specific area (hence, the "—" ranking in the Generic attribute in Table 1) while Framework B is a general-purpose one (hence, the "+" ranking in the Generic attribute in Table 1). Framework A enables distributed usage and Framework B is more focused on local usage. Framework A explicitly describes KM lifecycle activities, using the terminology creation, linking, sharing, maintenance, acquisition, filtering, indexing and categorization, whereas Framework B focuses on decision models in accordance with Nonaka's model [20] of knowledge creation, thus ranked "partial" on knowledge lifecycle activities. EIS is mentioned in Framework B but not in Framework A. Internet orientation is mentioned in Framework A but not in Framework B. There is no mention of automated decision-making collaboration in Framework A, other than discussing tools that help retrieving knowledge from the knowledge base, while Framework B does foster automated tools for sharing of decision models. The security and billing attribute is featured only by Framework A that deals with its relevant stakeholders. Both frameworks aim at supporting decision-making by different stakeholders (hence the positive DSS ranking for both), but only Framework A explicitly considers stakeholders as an inherent part of its model. Finally, both frameworks are ranked positively with regard to the CBR and the recommendations attributes.

4.2. Framework C: consolidating Frameworks A and B

Framework A emphasizes global and specialized KM for distributed stakeholders who share a central knowledge base via an infrastructure that facilitates retrieving relevant knowledge during crisis situations in real time [33]. Framework B addresses the need for collaboration with regard to modeling knowledge within a general-purpose decision support environment [4]. Neither KM framework alone, however, suffices for analyzing the CAIB report due to non-delivery of some desirable KM attributes. We therefore propose consolidating Frameworks A and B in Framework C, taking the generic view of Framework B, transforming its local perspective to a global one, and enhancing with a general-purpose perspective special-purpose Framework A components. Furthermore, as in Framework A, the Internet serves as a communication enabler and access channel in Framework C.

The *knowledge base* component at the core of Framework C (Fig. 3) holds internal and external data sources like databases and data warehouses, as well as internal and external knowledge sources like functional knowledge, organizational knowledge, and problem-specific knowledge [18]. In addition to including domain ontology

Table 1
Comparison of KM attributes delivered by Frameworks A and B.

Attributes	Framework A	Framework B
Distributed	+	—
Knowledge base	+	+
Knowledge lifecycle activities	+	Partial
DSS	+	+
CBR	+	+
Recommendations	+	+
Internet infrastructure	+	—
Connection to people	+	—
Security and billing	+	—
Generic	—	+
EIS	—	+
Automated decision models collaboration	—	+

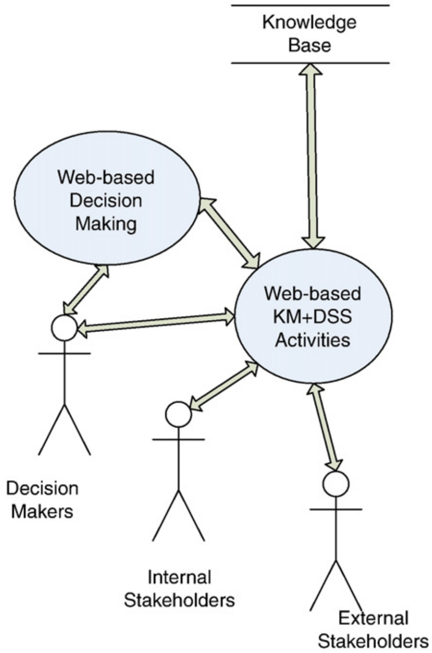

Fig. 3. KM components of Framework C.

and personal contact information, the knowledge base is enhanced with data mining, OLAP and search functionalities. Framework C's *web-based KM + DSS activities* component facilitates creating, sharing, categorizing, indexing, filtering, acquiring, maintaining, and linking of knowledge. This component is enhanced with machine-learning techniques that can automatically organize and mobilize knowledge in the knowledge base, via a web-based platform. It also includes KM tools like: web client agents; case-based reasoning, new model construction and integration; shared space for decision makers' interactions; information retrieval; recommendations; situational awareness that uncover perceptions, comprehensions and projections; and multimedia digitizing technologies. This knowledge infrastructure enhances *web-based decision-making* by *decision makers* as well as *internal* and *external stakeholders*.

5. CAIB report content analysis via the lens of Framework C

5.1. Categorization process

The process of content analysis revealed that Chapters 5 and 6 (in Part 2 of the CAIB report) include the most relevant text for the analysis pertaining to diagnosed problems, termed *problem-oriented* chapters hereinafter, and that Chapters 9, 10 and 11 (in Part 3 of the CAIB report) include the most relevant text for the analysis pertaining to prescribed recommendations, termed *recommendation-oriented* chapters hereinafter. It is noteworthy that in the former problem-oriented chapters, decision-making processes are referred to directly upon discussing the diagnosed problems. Yet, in the latter recommendation-oriented chapters, decision-making processes are referred to indirectly upon discussing the prescribed recommendations, without explicit mentioning of decision-making processes.

In the analysis described above in Section 3.2, 198 segments were identified, enumerated, coded and categorized. The enumeration number consists of a sequential segment number (S) from 1 to 198 and a page number (P), for example S9-P108 is the 9th segment identified on page 108 of the report, allowing the researchers to systematically return to the data upon need. The analysis process is demonstrated by the segment examples in Table 2. For each identified segment we present its enumerated number, following the quotation taken from the CAIB report and its open code. The categorization process involved aggregating related codes to categories for which either a corresponding KM attribute could be found within Framework C or to new emergent category created. Finally all the categories were mapped to Framework C components.

Mapping the categories to Framework C components suggests how Framework C may enhance decision-making processes. In the case of Segment S9-P108 and Segment S27-P123, Decision Support Systems (DSS) might have prevented both phenomena by perhaps enforcing checks and balances procedures, in the case of S9-P108, and follow-up procedures, in the case of S27-P123. In the case of Segment S57-P130 and Segment S77-P139, while both segments were coded to human aspects of decision-making processes, no corresponding KM attribute could be found within Framework C. Therefore, a newly emergent 'decision-making human factors' category was defined for both. Since the next step was to map the thus emerged KM category into a KM component of Framework C, the emergent category, encompassing all the codes that relate to human aspects of decision making processes that might lead to wrong decisions, was mapped to a correlated KM component (web-based KM + DSS activities — in particular explicitly managing decision models) of Framework C. This process helped trace KM components of Framework C that are implicitly discussed in the CAIB report.

The next section describes the categories revealed in the problem-oriented and recommendation-oriented segments of the CAIB report.

5.2. Findings

Out of the 198 identified segments, 61 segments corresponded to four of attributes of Framework C (see Table 1 above): distributed, connection to people, DSS, and knowledge base. Table 3 presents

Table 2
Illustration of the CAIB report content analysis.

Number	Text	Code	Category	Emergent	Component
S9-P108	"Garcia's particular concern was NASA's efforts to delete the 'checks and balances' system of processing Shuttles as a way of saving money."	Checks and balances system	DSS	No	Web-based KM + DSS activities
S27-P123	"After the mission was completed, the Program Requirements Control Board cited the foam loss as an In-Flight Anomaly. Citing an event as an In-Flight Anomaly means that before the next launch, a specific NASA organization must resolve the problem or prove that it does not threaten the safety of the vehicle or crew."	Definition without follow up	DSS	No	Web-based KM + DSS activities
S7-P130	"Assessments of foam-shedding and strikes were not thoroughly substantiated by engineering analysis, and the process for closing In-Flight Anomalies is not well-documented and appears to vary. Shuttle Program managers appear to have confused the notion of foam posing an 'accepted risk' with foam not being a 'safety-of-flight issue'. At times, the pressure to meet the flight schedule appeared to cut short engineering efforts to resolve the foam-shedding problem."	Engineers' confusion as a result of budget preferences	Decision making human factors	Yes	Web-based KM + DSS activities
S77-P139	"These little pieces of risk add up until managers are no longer aware of the total program risk, and are, in fact, gambling."	Managers' risk unawareness	Decision making human factors	Yes	Web-based KM + DSS activities

Table 3
Decision-making categories corresponding to KM attributes of Framework C.

Category	Definition	Illustrative problem-oriented segment	Illustrative recommendation-oriented segment	KM component
Distributed	The management structure is distributed, and the decision makers are scattered in many places. This includes also organizational complexity, authority structure and working relationships	"The space agency moved management of the Space Shuttle Program from the Johnson Space Center to NASA Headquarters in Washington, D.C […] NASA human space flight centers each retained their own safety organization reporting to the Center Director." S1-P101	"One is separating technical authority from the functions of managing schedules and cost. Another is an independent Safety and Mission Assurance organization" S167-P208	Internal stakeholders
Connection to people	The influence of external stakeholders on decision-making processes	"Flawed decision-making, self deception, introversion and a diminished curiosity about the world outside the perfect place" S5-P118	None	External stakeholders
DSS	Systems that can enhance decision-making processes	"Efforts to delete the 'checks and balances' system of processing shuttles as a way of saving money" S9-P108	None	Web-based KM + DSS activities
Knowledge base	Building a shared knowledge base	"[…] it is necessary to merge the required NASA and contractor skill bases." S12-P109	"Digitize the closeout photograph system so that images are immediately available for on-orbit troubleshooting" S192-P217	Knowledge base
Distributed	The management structure is distributed, and the decision makers are scattered in many places. This includes also organizational complexity, authority structure and working relationships	"The space agency moved management of the Space Shuttle Program from the Johnson Space Center to NASA Headquarters in Washington, D.C […] NASA human space flight centers each retained their own safety organization reporting to the Center Director." S1-P101	"One is separating technical authority from the functions of managing schedules and cost. Another is an independent Safety and Mission Assurance organization" S167-P208	Internal stakeholders
Connection to people	The influence of external stakeholders on decision-making processes	"Flawed decision-making, self deception, introversion and a diminished curiosity about the world outside the perfect place" S5-P102	None	External stakeholders
DSS	Systems that can enhance decision-making processes	"Efforts to delete the 'checks and balances' system of processing Shuttles as a way of saving money" S9-P108	None	Web-based KM + DSS activities
Knowledge base	Building a shared knowledge base	"[…] it is necessary to merge the required NASA and contractor skill bases." S12-P109	"Digitize the closeout photograph system so that images are immediately available for on-orbit troubleshooting" S192-P217	Knowledge base

these four revealed categories along with definitions, illustrative problem-oriented and recommendation-oriented segments of the CAIB report, and mapped-to KM components of Framework C. For example, in the third row of Table 3 the third revealed category (DSS), for which a corresponding attribute (DSS) could be found in Framework C, is listed, defined, illustrated with the problem-oriented segment S9-P108 (see Table 2 above), and mapped to a component (Web-based KM + DSS Activities) of Framework C.

Table 4
Emergent decision-making categories correlating to KM components of Framework C.

Category	Definition	Illustrative problem-oriented segment	Illustrative recommendation-oriented segment	KM component
Decision-making standards	Standards that should support decision-making processes	"United Space Alliance would have to meet a series of safety 'gates'". S11-P108	"Kennedy Space Center should examine which areas of International Organization for Standardization 9000/9001 truly apply to a 20-year- old research and development system like the Space Shuttle." S183-P220	Web-based KM + DSS activities
Control processes	Processes that can support decision-making (e.g. controlling, comparing, future analysis, risk management)	"This shifting date for Shuttle replacement has severely complicated decisions […]" S14-P111	"[…] will build a disciplined , systematic approach to identifying, analyzing, and controlling hazards throughout the life cycle of the Shuttle System." S189-P227	Web-based KM + DSS activities
Integrative approach	The decision-making processes that encompass people, technology and processes	"The specific ways in which this complexity and lack of an integrated approach to Shuttle management […]" S20-P118	"This recertification must be rigorous and comprehensive at every level […]" S170-P209.	All KM components of Framework C
Communication	The way people communicate during decision-making processes	"Communication of problems and concerns upward to the SSP from the 'floor' also appeared to leave room for improvement" S16-P114	"[…] Such factors interfere with open communication, impede sharing of lessons learned, cause duplication and unnecessary expenditure of resources […]" S169-P208	Web-based decision-making
Decision-making human factors	The human factors that influence decision-making processes	"These little pieces of risk add up until managers are no longer aware of the total program risk, and are, in fact, gambling." S77-P139	None	Web-based KM + DSS activities — in particular explicitly managing decision models
Decision-making in action	The decision taken during decision-making processes	"NASA and contractor personnel came to view foam strikes not as a safety-of-flight issue, but rather a simple maintenance, or 'turnaround' issue". S26-P122	None	Web-based decision-making

Out of the 198 identified segments, 137 segments corresponded to no Framework C's attributes, leading to definition of six newly emergent categories: decision-making standards, control processes, integrative approach, communication, decision-making human factors, and decision-making in action. The six categories are similarly presented in Table 4 along with definitions, illustrative problem-oriented and recommendation-oriented segments of the CAIB report, and correlated KM components of Framework C that the emergent categories are respectively mapped to. For example, the fifth row of Table 4 lists the fifth emergent category (decision-making human factors), defined in the absence of a corresponding KM attribute in Framework C, illustrated with the problem-oriented segment S77-P139 (see Table 2 above), and mapped to a correlated component of Framework C (Web-based KM + DSS — in particular explicitly managing decision models).

Fig. 4 presents the CAIB revealed categories vis-a-vis the components of Framework C. The four categories that correspond to matched attributes of Framework C (knowledge base, DSS, connection to people, and distributed) are marked in green and connected to the correlated components of Framework C (knowledge base, web-based KM + DSS activities, external stakeholders and internal stakeholders). Five emergent categories (decision-making standards, control processes, decision-making human factors, communication, and decision-making in action) are marked in yellow and are connected to mirrored components of Framework C (web-based KM + DSS activities and web-based decision-making) with dotted lines in the absence of matched corresponding attributes in Framework C. Exceptionally, one emergent category (integrative approach) is not connected to any component of Framework C because it refers to Framework C as a whole rather than to a specific component.

As explained above, the content analysis distinguished between problem-oriented segments and recommendation-oriented segments in the CAIB report. This distinction is important for examining whether, in the context of knowledge management, recommendations prescribed for avoiding future problem recurrence indeed address all problems diagnosed in the CAIB report. With this distinction in mind, Fig. 5 presents the distribution of problem-oriented (172 segments) and recommendation-oriented (26 segments) segments according to the revealed categories.

As shown in Fig. 5, six of the 10 categories (distributed, knowledge base, decision-making standards, control processes, integrative approach, and communication), are discussed in both problem-oriented and recommendation-oriented segments. Four of the 10 categories (connection to people, DSS, decision-making human factors, and decision-making in action), on the other hand, are discussed only in the problem-oriented segments but not in the recommendation-oriented segments. It should be noted that decision-making human factors refer to human rationalism that stood behind decisions rather than to cultural or organizational pressures that decision makers were facing. This is illustrated in S119-P157: "[…] Rocha replied that he did not want to jump the chain of command." Fig. 5 also shows that problem-oriented segments of the CAIB report deal mainly with communication, control processes, and decision-making human factors. On the other hand, recommendation-oriented segments deal mainly with knowledge base, decision-making standards and control processes.

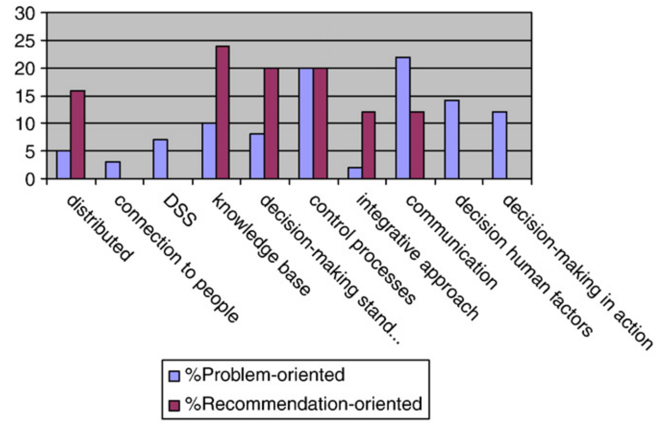

Fig. 5. The distribution of segments vis-à-vis the revealed categories.

6. Discussion

Before discussing the findings, it is important to acknowledge the limitations of the current research due to incomplete access to data. For instance, components like case-based reasoning, security and billing were not covered in the CAIB report and therefore were not included in the analysis. In addition, without access to current decision-making processes at NASA, our findings are applicable only

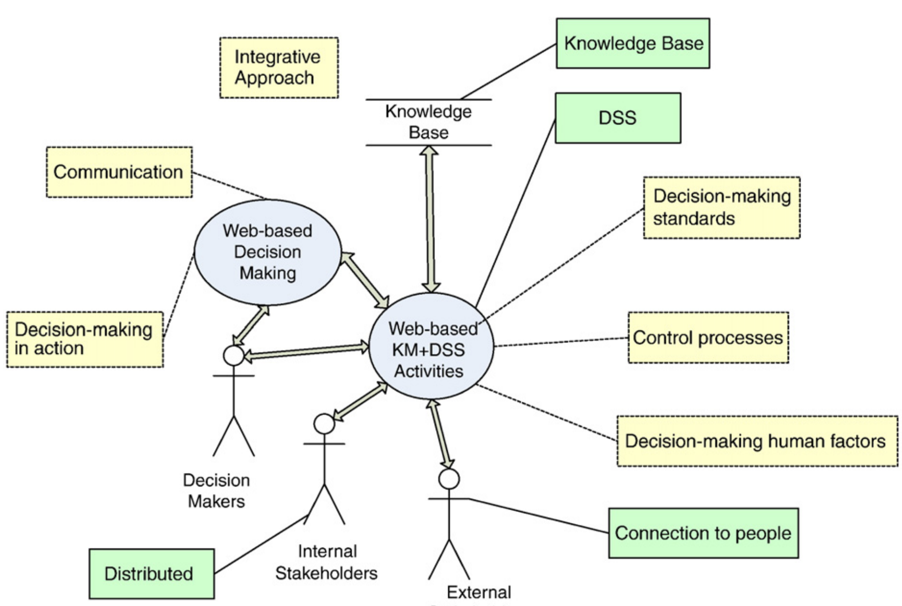

Fig. 4. The CAIB revealed categories vis-à-vis the components of Framework C.

in the context of the CAIB report. Nevertheless, the CAIB report has been useful for accomplishing our aim to analyze decision-making processes in organizations via the lens of a generic KM framework.

The previous section's findings emanate from analyzing decision-making processes that occurred before and during Columbia's flight via the lens Framework C. According to Fig. 5, KM categories are discussed in the recommendations of CAIB report either explicitly (6 out of 10) or implicitly (4 out of 10), pointing to the question of whether better knowledge management practices could have prevented the Columbia explosion. While trying to provide a definite answer to this question would be speculative, it is worthwhile to discuss whether and how the components of Framework C could have enhanced decision-making processes and perhaps reduce the explosion risk. For demonstration purposes, the following discussion, of how explicit knowledge management practices might have contributed to better decision-making processes, is grounded in two decision scenarios taken from the CAIB report.

Decision Scenario 1 deals with the decision, before the Columbia flight, to regard the foam-shedding as an inevitable and acceptable risk (Page 122), even though foam loss was considered dangerous (Page 121). Although "the Program Requirements Control Board Chairman assigned an 'action' to the External Tank Project to determine the root cause of the foam loss […] The Space Shuttle Program decided to fly two missions before resolving the STS-112 foam loss." (Page 125). Moreover, events that occurred before the Challenger and Columbia explosions were also related to foam loss (Page 123). Evidently, the decision to regard the foam loss as an inevitable acceptable risk suffered from disregarding ten years of experiencing foam loss: "Assessments of foam-shedding and strikes were not thoroughly substantiated by engineering analysis…In-Flight Anomalies is not well-documented and appears to vary." (Page 130). Another observation about Decision Scenario 1 is that there was neither a standard decision-making process in place, nor a systematic process for taking into account different views and considerations due to lack of communication within NASA authority structure: "…Communication of problems and concerns upward to the SSP from the 'floor' also appeared to leave room for improvement" (Page 114).

Implementing the web-based KM + DSS activities component of Framework C, in Decision Scenario 1, could have facilitated more standard and collaborative decision-making processes by allowing automated knowledge retrieval processes regarding similar foam-related events. Within the distributed organization, having the various stakeholders communicate via a web-based decision-making component, might have fostered joint open discussions, possibly encouraging engineers to provide insights regarding the foam-loss concerns. Furthermore, in the spirit of Framework C, decision-making processes are recorded for future practice. Such recording requires managers to explicitly explain in full the rationale behind any decision and, hopefully, refrain from decision-making based on wrong subjective beliefs and inappropriate data. In the Columbia case: "The assumptions and uncertainty embedded in this analysis were never fully presented to the Mission Evaluation Room or the Mission Management Team" (Page 145). The control attribute of the web-based KM + DSS activities component, could have enforced regulations that might have prevented flying any shuttle until the resolution of the foam-shedding risks (Page 126).

Decision Scenario 2 deals with the decision, during the Columbia flight, to decline imagery requests for determining potential damage, after realizing that a large piece of debris did strike the Orbiter so late in ascent (Page 140). According to the CAIB report, at least eight imagery requests that came from NASA engineers and managers were declined without any systematic and collaborative decision-making processes. This imagery decline decision was made without awareness of assessments and concerns raised by the members of the Mission Evaluation Room, as recorded in their running log (Page 141), since neither this log nor any other input from these engineers was available to the managers during their decision-making processes. In addition, the Debris Assessment Team, while being the right group of analysts to analyze the imagery requests, was not classified as the Tiger Team and left outside the decision process (Page 142). Finally, many of the discussions were held through emails, leading to wrong communication patterns.

Implementing the knowledge base component of Framework C along with the web-based KM + DSS activities component, in Decision Scenario 2, could have exposed the professional insights of other groups to decision makers throughout NASA. Also, communication difficulties could have been avoided with the help of the web-based decision-making component of Framework C. This collaborative environment could have been utilized for enabling various stakeholders to share opinions and reduce communication barriers caused by organizational and authority structures.

The mapping of the revealed categories into KM components of Framework C, as demonstrated by Decision Scenarios 1 and 2, highlights whether and how the components of Framework C could have enhanced and improved decision-making processes and perhaps reduce the explosion risk. In particular, the web-based decision-making component could have better connected internal and external stakeholders, the web-based KM + DSS activities component could have supported decision models as well as enable critique of decision makers' decision models, and the knowledge base component could have facilitated shared knowledge.

Fig. 5 above, allows us to detect a gap between the problems diagnosed in the CAIB report and the recommendations prescribed. The recommendations deal mainly with the knowledge base, decision-making standards, communications and control processes. Also noteworthy is the relatively high percentage of recommendation-oriented segments in the distributed and integrative approach categories, compared to the problem-oriented segments. Yet, while implicitly addressing KM components, the recommendations neither explicitly advocate adoption of KM components nor provide a practical way of coping with the decision-making human factors and communication issues that the report associates with many of Columbia's problems.

Our analysis of decision-making processes via Framework C not only illustrates the need for a generic KM framework, but is in line with Rubenstein-Montano et al. [25] who claim that there is a need for a codified, generally accepted KM framework that relates to organizational strategies and goals. While they refer to a general KM framework, this paper fosters a KM framework designated to support decision-making processes.

While most KM frameworks are utilized during design of KM initiatives within organizations, the comprehensive KM framework developed in this study was used for analyzing pre-explosion decision-making processes and the post-explosion CAIB recommendations. Such an integrative analysis approach can suggest a roadmap for enhancing decision-making processes in the future.

7. Conclusions and recommendations

In a strategic plan for KM, which had been written before the Columbia accident, NASA acknowledged that its knowledge and intellectual capital is the agency's primary sustainable source of competitive advantage [11]. Furthermore, KM was recognized as the spark that could ignite NASA's ability to get the most out of investments made in the workforce and in information technology via exploitation of intellectual capital within the agency and beyond. A KM initiative was established, aimed at enhancing the flow of experiential and tacit knowledge for the sake of safely conducting missions. The main objectives of the KM initiative were to enable collaborative and efficient work of virtual teams; effective capturing, management, and provision of access to information for making the best decisions possible toward mission safety and success; and making NASA's knowledge sustainable across missions and generations [11].

Our analysis illustrates, based on the CAIB report, the gap between NASA's strategic KM plan and its implementation in the context of Columbia's shuttle explosion. It also provides evidence for the need to incorporate KM practices into decision-making processes. However, although the CAIB report linked problems in decision-making processes that took place before and during the flight with the explosion, their recommendations hardly address directly and explicitly knowledge management in decision-making processes per se. Since the research data lacks information regarding the current situation in NASA, our conclusions are relevant to the period of Columbia's flight and not to the current situation. Still, we claim that analyzing decision processes through a KM lens is applicable to other companies and we use the NASA case study to illustrate it.

Our research examined several KM frameworks for decision-making processes and proposed a consolidated KM framework C, based on two major frameworks that differ in their perspectives, as broadly discussed in Section 4 above. The consolidated framework represents a significant contribution since it is more robust than each parent framework alone and allowed a comprehensive analysis of the case facts that addressed issues related to knowledge transfer in a distributed environment; managing the whole knowledge lifecycle activities; and handling decisions and decisions rationalism. Left for future research is a more comprehensive literature review regarding KM frameworks that support decision-making processes, aiming to establish a more general KM framework for decision-making processes in diverse organizations.

Practitioners may consider either using KM Framework C as a diagnostic tool, toward effective knowledge creation in the decision-making processes [26], or adopting KM Framework C for improved and enhanced decision-making processes, by enabling knowledge retrieval; facilitating objective negotiations; supporting solution inquiry; and leveraging group communication. Based on this work, we have good reason to believe that systematic KM diagnostics in the context of business decision-making processes may facilitate overcoming the gap between theoretical KM frameworks and KM implementations and, eventually, may lead to realizing the benefits of implementing a KM framework in promoting embedded KM practices in decision-making processes.

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