NASA/TM—2017–219539

Autonomous, Context-Sensitive, Task Management Systems and Decision Support Tools II: Contextual Constraints and Information Sources

Barbara K. Burian
NASA Ames Research Center

Janeen A. Kochan
Aviation Research, Training, and Services

Kathleen L. Mosier
San Francisco State University

Ute Fischer
Georgia Institute of Technology

September 2017

NASA STI Program…in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, and organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question via to help@sti.nasa.gov

- Phone the NASA STI Help Desk at (757) 864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM—2017–219539

Autonomous, Context-Sensitive, Task Management Systems and Decision Support Tools II: Contextual Constraints and Information Sources

Barbara K. Burian
NASA Ames Research Center

Janeen A. Kochan
Aviation Research, Training, and Services

Kathleen L. Mosier
San Francisco State University

Ute Fischer
Georgia Institute of Technology

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California

September 2017

Trade name and trademareks are used in this report for identification only. Their usage does not constitute an official endoresement, either expressed or implied, by the National Aeronautics and Space Administration.

Available from:

NASA STI Program
STI Support Services
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

This report is also available in electronic form at http://www.sti.nasa.gov
or http://ntrs.nasa.gov/

Table of Contents

Acronyms and Definitions

2D	2-dimensional
3D	3-dimensional
A4A	Airlines for America
AGL	above ground level
AOA	angle of attack
AP	autopilot
AQP	Advanced Qualification Program
ATA	Air Transport Association
ATC	air traffic control
CAS	calibrated air speed
CFR	Code of Federal Regulations
CIAIAC	Comision de Investigacion de Accidentes e Incidentes de Aviacion Civil
DME	Distance Measuring Equipment
E&E	electrical and environmental bay
ECAM	Electronic Centralized Aircraft Monitoring System
EICAS	Engine Indicating and Crew-Alerting System
FAA	Federal Aviation Administration
FL	flight level
FMS	flight management system
FPM	flight path management
FPMSC	Flight Path Management Steering Committee
ft	feet
GPS	global positioning satellite system
IA	inspection authorization
ILS	instrument landing system
MEL	minimum equipment list
MMEL	Master Minimum Equipment List
MSL	mean sea level
NASA	National Aviation and Space Administration
NAV	naviation
Navaids	navigation aids
NTSB	National Transportation Safety Board
O_2	oxygen
PBN	performaced-based navigation
QRH	quick reference handbook
RAIM	Receiver Autonomous Integrity Monitoring
RNAV	Area Navigation
RPM	revolutions per minute
RTCA	Radio Technical Commission for Aeronautics
VOR	VHF (very high frequency) Omni-directional Radio-range

Figures and Tables

Autonomous, Context-Sensitive, Task Management Systems and Decision Support Tools II: Contextual Constraints and Information Sources

Barbara K. Burian[1], Janeen A. Kochan[2], Kathleen L. Mosier[3], and Ute Fischer[4]

1. Introduction

Advanced automation and autonomous systems have been increasingly used to reduce pilot workload, help them better manage their tasks, and support their decision making during both normal and non-normal operations (Banks & Lizza, 1991; Champigneux, 1995; Matheus et al., 2005). Unfortunately, these systems and tools have often in the past led to pilot confusion (Mosier & Skitka, 1996; Sarter, Woods, & Billings, 1997) or have been narrowly developed and have failed to fully support and address the pilots' needs (Banks & Lizza, 1991; Miller & Hannen, 1999). However, recent advances in artificial intelligence, machine learning, data mining and extraction, and especially in sensor technology have resulted in the availability of a vast amount of digital data and information and the development of advanced automated reasoners. This creates the opportunity for "the development of a robust dynamic task manager and decision support tool that is context sensitive and integrates information from a wide array of on-board and off aircraft sources—a tool that monitors systems and the overall flight situation, anticipates information needs, prioritizes tasks appropriately, keeps pilots well informed, and is nimble and able to adapt to changing circumstances" (Mosier, Fischer, Burian, & Kochan, 2017, p. 6).

This is the second of two companion reports exploring issues associated with autonomous, context-sensitive, task management and decision support tools. In the first report (Mosier et al., 2017), we explored fundamental issues associated with the development of an integrated, dynamic, flight information and automation management system. We discussed human factors issues pertaining to information automation and reviewed the current state of the art of pilot information management and decision support tools. We also explored how effective human-human team behavior and expectations could be extended to teams involving humans and automation or autonomous systems.

In this report, we extend this work to focus on two critical aspects of integrated, dynamic, flight information and automation management systems: 1) the constraints and conditions that drive the dynamic prioritization and presentation of data and information to the pilots, and 2) specific data and information to be accessed, monitored, integrated, and displayed in such a system. Although most of the topics discussed in the companion report (Mosier et al., 2017) have wide applicability to many work domains where information automation and autonomous systems are used, this document

[1] NASA Ames Research Center.
[2] Aviation Research, Training, and Services.
[3] San Fracisco State University.
[4] Georgia Institute of Technology.

focuses on issues specific to the aviation domain and particularly to the flight deck. Even so, the topics reviewed in this report (e.g., relevant constraints and conditions) can be modified for extension and application to other socio-technical work domains.

As in the companion report (Mosier et al., 2017), in this document we will use the terms "automation," "autonomous systems," and "agents" interchangeably, even though they are technically distinct from one another. Additionally, we refer to human actors only as "humans" and use the term "agent" only to refer to highly sophisticated automation and autonomous systems. Additionally, for simplicity, "dynamic, integrated information, task management and decision support tool" will often be referred to as "the system" or "the tool" throughout this document.

2. Contextual Constraints and Conditions

As has been described elsewhere (Burian, Mosier, Fischer, & Kochan, in press; Burian & Martin, 2011) and in the companion report to this document (Mosier et al., 2017), pilots currently must access, interpret, and integrate a large amount of data and information from a wide variety of sources to perform even some of the most basic flight tasks. Some of this data and information change dynamically, moment by moment, such as flight instrument and navigation displays, flight deck cues and alerts (Berman et al. 2017), weather radar and environmental conditions, surrounding aircraft traffic and terrain, and clearances and information received from air traffic control (ATC). Other information is static but can be changed as it is edited or updated (though not in real time) such as navigation charts and procedures and checklist items. Yet other information, such as that included in aircraft performance tables and systems manuals, never changes (absent an emergency or non-normal event) once an aircraft has been developed and certified. Some of this data and information, whether dynamic or static, exist on-board or come from the aircraft itself while other data and information come from off-aircraft sources (Bailey, Prinzel, Kramer, & Young, 2011).

A significant task then, for developers of decision support systems, is to determine what data and information are relevant at a particular time (Abbott, McKenney, & Railsback, 2013) and to "…integrate, summarize, distribute, format, abstract, prioritize, categorize, calculate, process, and display [that] information in a variety of ways to support flight crew tasks" (Letsu-Dake et al., 2015, p. 3D1). Moreover, the system should neither overwhelm the pilots (Abbott et al., 2013; Letsu-Dake et al., 2015) nor compromise their situation awareness (Durso & Sethumadhavean, 2008; Endsley, 2000). In other words, information supporting pilot task management should be automatically made available when it is needed, be trustworthy and clearly interpretable, and non-relevant information should be withheld or suppressed (Bailey et al., 2011; Mosier et al., 2017).

In our companion report (Mosier et al., 2017), we identified a number of fundamental decisions that must be made by the developers of these systems prior to the initiation of development. These decisions, in part, pertain to the answers to the following questions:

- What pilot cognitive processes (e.g., attention, information integration, analysis, option generation) should be supported by the system?
- What is the appropriate level of support that the system should provide? In other words, how directive should the guidance be and should the system be able to autonomously complete certain actions, especially when pilots do not complete a critical task within a specified period of time?
- How would different types of data and information best be presented?

- Which types of information should be constantly displayed (if any), which should be automatically displayed when relevant/needed, and which (if any) should never or rarely be displayed automatically but available for access whenever it is desired by the pilot?
- Who or what should control the flow of information?
- What factors should be taken into account at any given moment to determine information relevance?
- How should relevant information be prioritized and should prioritization schemes be able to change moment-by-moment? If so, what factors should drive this re-prioritization and how should information be displayed during re-prioritization so that pilots do not become confused or "get lost"?

The answers to some of these questions, particularly those in the last two bullets, are partially determined by the constraints and conditions that exist moment-by-moment throughout the flight, the relative values placed on these constraints by the developers, and their association with tactical and strategic pilot task management and decision making requirements (Burian & Martin, 2011; Burian et al., in press). A constraint, by definition, imposes a limitation on or defines what tasks can or should be accomplished at a particular time—and, by extension, what information is needed. Constraints are a function of the many dynamic contextual conditions and situations that exist with the passage of time. Constraint values (i.e., statuses) are used in conjunction with if-then algorithms, fuzzy and Bayesian logic, machine learning and artificial intelligence to develop automated reasoners, which drive the system behavior regarding what information is needed, when it is needed, and how it should be prioritized (Abbott, Jones, Consiglio, Williams, & Adams, 2004; Burian et al., in press; Estes et al., 2016). Therefore, one of the early steps in the process of developing such a tool to support flight operations is to identify the various constraints and conditions that might exist over the course of a flight; we have identified 11 such inter-related categories of constraints and conditions (see Table 1; Burian et al., in press; Mosier et al., 2017). Most of these constraints exist concurrently and it is the myriad of ways in which their dynamic values may be combined and interact that makes these systems such powerful tools but also which makes their development so challenging. We explore each of these 11 constraints in more depth below.

Table 1. Flight Operations Constraints and Conditions

Constraint or Conditions	*As a Function of*	*Types*	*System Functioning*
Time		• Amount of time until X (countdown timer) • Amount of time since X (count up timer) • Time window during which X can occur or be accomplished	• Monitors the passage of time relative to flight schedule, phases of flight, and progress along route of flight • Monitors windows during which X condition can occur or X task can be, or is most appropriately, accomplished • Monitors length of time pilot/operator takes to accomplish actions/tasks presented on system displays • Displays information that is tailored to the situation & tasks to be accomplished • Prompts pilot/operator to take action
Risk		• Safety risk • Economic risk • Productivity	• Monitors flight parameters and compares against pre-determined limits for operation of aircraft and company policies and procedures • Displays information that is tailored to the situation providing relative "closeness" to exceeding established criteria (once a particular threshold has been met) • Prompts pilot/operator with which action(s) to achieve flight behavior/ parameters that are within desired "risk" envelope
Pilot/operator characteristics, workload and psycho-physiological state	• Lengths (L) and complexity (C) of N tasks to accomplish in time (T) • Measured physiological parameters	• Procedure and task length and complexity • Alertness, duty time, circadian rhythm, fatigue, work schedule (which leg in the trip, how many trips back to back, hours of rest) • Pilot physical health • Pilot experience on aircraft type and with equipment/automation • Pilot training status	• Monitors pilot/operator workload and sensed psychophysiological states • Displays information and integrates to support decision making • Prioritizes information and suggested actions based upon task importance • Suggests which tasks to shed, if necessary, during extremely time critical situations • Takes over pre-determined tasks
Aircraft system and component status		• Gear, flaps, spoilers, elevators, ailerons, brakes • Electrical system and E&E bays, hydraulics, pressurization, air systems, engines, oil, fuel • Doors, windows, access panels, lavatories, galleys, cargo/cargo bay • Computers, displays, inflight entertainment system, sensors, alerting system, communication systems, radios, navigation equipment	• Monitors and indicates system and component status, malfunctions, and failures • Calculates impact on: planned route of flight, expected aircraft performance, flight parameters, aircraft integrity and airworthiness, and informs pilot/operator; suggests tasks/actions as needed

(continued on next page)

Table 1. Flight Operations Constraints and Conditions *continued*

Constraint or Conditions	*As a Function of*	*Types*	*System Functioning*
Aircraft system and component status		• Gear, flaps, spoilers, elevators, ailerons, brakes • Electrical system and E&E bays, hydraulics, pressurization, air systems, engines, oil, fuel • Doors, windows, access panels, lavatories, galleys, cargo/cargo bay • Computers, displays, inflight entertainment system, sensors, alerting system, communication systems, radios, navigation equipment	• Monitors and indicates system and component status, malfunctions, and failures • Calculates impact on: planned route of flight, expected aircraft performance, flight parameters, aircraft integrity and airworthiness, and informs pilot/operator; suggests tasks/actions as needed
Phase of flight	• Time • Location	• Amount of time until X • Amount of time since X • Time window during which X can occur or be accomplished • Procedures (relative to location and phase of flight)	• Monitors passage from one phase of flight to another and compares against flight schedule and clearance; suggests changes/actions, if needed • Uses phase of flight and time to guide presentation of information and actions from checklists and procedures • Tailors information to the needs of the flight phase tasks
Regulations, procdures, company procedures and policies		• Adherence to industry and company policies and procedures such as: – stable approach criteria – PBN criteria – RNAV departure and approach criteria – precision approach criteria, etc.	• Monitors aircraft behavior and flight progress and compares against industry, aircraft operating, and company policies and procedures • Informs pilot/operator if the system is unable to operate the aircraft according to the criteria and why • When deviating from policies/ procedures during manual flight, informs pilot/operator of deviation and what action(s) to take to get back into compliance with policies and procedures • Informs pilot of possible consequences for specific deviation from policies/procedures when such a deviation exists (during both automated and manual flight)

(continued on next page)

Table 1. Flight Operations Constraints and Conditions *continued*

Constraint or Conditions	*As a Function of*	*Types*	*System Functioning*
Flight parameters	Time *and* phase of flight *and* adherence to policies/ procedures	• Altitude • Heading • Indicated airspeed • Ground speed • Vertical speed • Distance from A (geographic location, airports, Navaids, terrain features, obstacles) • Progress on route • Datacomm/radio and navigation frequencies • Altimeter settings • Transponder codes	• Monitors flight parameters and compares against aircraft capabilities and limitations, flight schedule, and clearance; informs pilot/operator and, if needed, suggests changes/actions • Automatically changes datacomm/radio and navigation frequencies, altimeter settings, and, if necessary, transponder codes and informs pilot of changes • Warns pilot when changes to flight parameters are imminent based upon route of flight or phase of flight changes
Equipage and maintenance status		• Aircraft equipment list (type of engines, autopilot, avionics suite, etc.) • FMS database version • Navigation database version • Maintenance history and logs • MEL'ed items	• Evaluates aircraft equipage (including MEL status) and equipment capabilities against go/no go criteria/MMEL, procedural requirements, and airworthiness directives and informs pilot of operational issues • In reference to version/update status of databases, MEL'd items, & maintenance history/logs, the system selects relevant non-normal checklist items for presentation (when needed) and informs pilot of any related operational issues

(continued on next page)

Table 1. Flight Operations Constraints and Conditions *continued*

Constraint or Conditions	*As a Function of*	*Types*	*System Functioning*
Environmental and external conditions		• Winds and turbulence • Weather and precipitation • Icing conditions and aircraft icing • Air pressure • Temperature and dew points • Airport location and status and runway conditions • Navaids (location and functioning status) • GPS/RAIM integrity • Traffic • Terrain • Other geographic features (bodies of water, cities) • Obstacles (towers, buildings, birds, animals on the runway, etc.) • Availability of ground services (ATC, dispatch, ground operators, maintenance facilities, emergency personnel, hospitals, etc.)	• Monitors environmental and external conditions and informs pilot/operator as appropriate; suggests actions as necessary • Compensates for effects of environmental and external conditions in determinations of/suggestions for revised flight path, approach to aircraft operation and procedures, alternate landing sites, etc.
Critical events	Time *and* pilot workload/psycho-physiological state *and one or more of the following:* Aircraft system/ component status, flight parameters, phase of flight, environmental/ external conditions	• Emergency situations • Abnormal situations • Delayed/compressed actions or maneuvers • Collision/near collision	• Informs pilot/operator that a situation outside of the realm of normal operations exists and what it is, with an initial assessment of level of criticality (emergency, abnormal, off-nominal) • If appropriate, displays system schematics with indication of non-normal state or conditions and effects of response actions (in real time) • Integrates appropriate information and actions from relevant checklists with actions required for overall situation management and presents for accomplishment/ consideration as appropriate or when relevant • Takes over some pre-determined tasks • Informs pilot/operator of aircraft limitations and capabilities relevant to remaining expected flight tasks
Aircraft habitability	Critical events *and* time	• Temperature • Atmospheric pressure • Smoke • Toxic fumes	• Monitors status of aircraft habitability and pushes information about maintenance of crew and passenger health as necessary • Suggests actions (e.g., donning O_2 masks and goggles, dropping passenger O_2 masks) as needed

2.1 Flight Operations Constraints and Conditions

2.1.1 Time

Time is the most inescapable and limiting constraint that exists in flight operations as well as operations in many other high consequence work domains (e.g., medicine, nuclear reactors, etc.). Most actions must occur at a particular time or during a "window of time" relative to other conditions or actions (Burian, Christopher, Fry, Pruchnicki, & Silverman, 2013). For example, in aviation, at least one engine must be started before an aircraft can begin to taxi. Similarly, a flight must receive an ATC clearance before it can (legally) takeoff and flight crews must lower the landing gear prior to the aircraft touching down on the runway (if they wish to avoid damaging the aircraft). Thus, pilot actions are dependent upon how much time has passed since some things have occurred, how much time remains before something else occurs, and/or the window of time during which a task can or must be accomplished.

Therefore, a dynamic, integrated information, task management and decision support tool must monitor the passage of time relative to a number of factors including the flight schedule, phases of flight, and progress along the route of flight and track the accomplishment of tasks in comparison to them. By this statement and through the rest of our discussion below it will become obvious that the constraint of time is highly related to almost all the other constraints in our list.

2.1.2 Risk

In flight operations, five types of risk have been identified: physical (i.e., safety), professional, productivity, economic, and social (Orasanu, Fisher, & Davison, 2004). In terms of constraints, we are concerned with safety risk, economic risk, and productivity risk. Some safety risks may be associated with relatively hard parameters such as those circumscribed by flight control laws (e.g., normal law[5]) or stabilized approach criteria. Other parameters are more "aspirational" and depend upon appropriate pilot judgment and behavior relative to air carrier or company policies. Economic risk during flight operations often depends upon human judgment and involves flight-related decisions that might increase costs, such as requesting a reroute that adds to fuel costs, or cause harm to the company's image and reduce repeat business, such as long delays or mishandled passenger disruptions. Some productivity risks overlap with economic risks, such as a reroute that not only adds to fuel costs but also increases the length of a flight. Other productivity risks pertain to actions or events that increase workload or are less efficient.

During the development of a dynamic, integrated information, task management and decision support tool, as much as possible, specific behavior and actions associated with safety, economic, and productivity risks—derived from procedures, policies, and pilot practices (Degani & Wiener, 1994)—will have to be identified and then quantitatively defined. The system will then use those definitions or "hard targets" when determining what information is needed and when relative to a given risk. For example, the system might automatically prompt the pilot for actions and decisions that fall within a pre-defined acceptable risk envelope or inform pilots when they are getting close to or have crossed over into unacceptable risk territory.

---

[5] Normal law is a control law that exists on Airbus fly-by-wire aircraft whereby flight computers provide flight envelope protection against unsafe pitch attitudes, bank angles, and overspeeding, among other things.

2.1.3 Pilot/Operator Workload and Psychophysiological State

Although currently somewhat limited, in the future, sensor or behavioral data associated with pilot workload and psychophysiological state may be available. These data could be used for determining information needs and the amount and kind of task support that might be necessary. Workload is the more easily defined variable, even today, as a function of the length, complexity and number of tasks that must be performed within a given period of time. Pilot psychophysiological state includes such things as alertness and physical and emotional health—aspects of pilot functioning that are currently difficult to automatically sense on the flight deck. Other factors associated with expected pilot functioning related to training status, level of experience, and work schedule are more easily captured for system use.

2.1.4 Aircraft System and Component Status

Today, the status of aircraft systems and components is heavily sensed in modern aircraft and sensor data drive the presentation of alerts, advisory messages, integrated electronic checklists (if equipped), and electronic system schematic information, as well as general system and component status, such as engine pressure ratio, oil temperature, amount of remaining fuel, and degree of gear and flap extension. These data could be easily incorporated into a dynamic, integrated information, task management and decision support tool.

2.1.5 Phase of Flight

Phase of flight is a function of time and aircraft location (both vertically and laterally) along a route, including taxiing and ground operations at airports. The different phases are relatively well defined in aviation (e.g., taxi out, cruise, approach) and can provide the framework or structure for a dynamic, information and task management system since specific tasks and procedures are associated with each phase.

2.1.6 Regulations, Procedures, Company Procedures and Policies

A variety of rules and expectations govern or guide what actions pilots carry out and when and how they are enacted. Some have the force of law, such as federal aviation regulations, or carry with them the expectation of strict adherence, such as altitudes and headings to fly during instrument departures and arrivals. Company dictated procedures and policies, such as stabilized approach criteria, also have the expectation of adherence though non-adherence generally resulting in fewer or lesser adverse costs.

Regardless of their source, regulations, all types of procedures, and company policies can be incorporated into a dynamic, integrated information, task management and decision support tool to guide pilot behavior and actions. One challenge for system developers, however, is to ensure that pilots understand which guidance based on these sources is expected to be more rigidly followed, except under exceptional circumstances such as an inflight emergency, and which may be more flexibly applied across many situations. In either case, it is important for the system to keep the pilot abreast of possible consequences for deviating from specific regulations, procedures, and policies relative to contextual factors that exist at the time.

2.1.7 Flight Parameters

"Flight parameters" refers to current aircraft performance (e.g., altitude, ground speed), as well as location (e.g., distance from a waypoint, progress on route), and various instrument settings (e.g., active radio frequencies, transponder code). Flight parameters are a function of the intersection of three other constraints: time, phase of flight, and adherence to regulations, policies, and procedures. As with aircraft system and component status, flight parameters are usually well sensed and/or indicated to pilots in current modern aircraft and could be easily incorporated into a dynamic, information and task management system.

2.1.8 Equipage and Maintenance Status

In contrast to flight parameters and aircraft system and component status, modern aircraft generally lack well sensed or clearly indicated information related to specific equipment aboard an aircraft (such as which version of avionics software is installed) or its maintenance status (e.g., how long until a "C" maintenance check is due, compliance with airworthiness directives). Some of this information has little relevance for pilots during their day-to-day operations so may appropriately be withheld or not made easily accessible. Other information has great relevance (e.g., minimum equipment list [MEL] status of equipment) but may only be available through reference to a handwritten logbook.

Similar information also has significant implications for flight operations. For example, pilots may need to know the model and brand of engines on the aircraft to determine the correct actions to take if one of them fails. Likewise, knowledge of an aircraft's equipage and its related capabilities is required to receive different levels of service under NextGen. Information such as this, as well as that currently in handwritten logs, could be integrated into and referenced by a dynamic, information and task management system so that only pertinent actions are presented and pilots are informed about NextGen service level availability.

2.1.9 Environmental and External Conditions

A wide range of environmental and conditions external to an aircraft has importance for flight operations and pilot decisions. These include winds, precipitation, convective activity, icing conditions, air pressure, aircraft traffic, terrain, obstacles, global positioning system (GPS) signal integrity, and the location and functionality of navigation aids (Navaids), among others. Known fixed features, such as mountains and towers, and sensed transitory features, such as aircraft traffic and weather conditions, are important additions to dynamic, information and task management system and decision support tools; the presence, status, or absence of these conditions over the course of a flight could have significant operational ramifications.

2.1.10 Critical Events

It is in helping pilots respond to and manage critical events that integrated, dynamic, information and task management system and decision support tools reveal some of their greatest value. Some critical events are transitory in nature (such as a near miss or a missed approach) or might even be relatively benign and easily dealt with (Burian, Barshi, & Dismukes, 2005). Other critical events can be quite perilous, however, and a well-designed information and task management system can help pilots prioritize their actions, focusing on that which is most essential moment by moment. At times these actions will be in direct response to the event and focus on fixing, "safeing," or taking a malfunctioning system off-line. At other times these actions will focus on "flying the aircraft" tasks, such as communicating with ATC, coordinating with company dispatch, or preparing for an emergency landing.

Different critical events pose different types of constraints: limiting or restricting some actions, adding others, and integrating them to be responsive to the demands of overall flight operations and the contextual factors that exist. Thus, critical events serve to constrain or shape information, task management, and decision support needs as a function of the amount of time that is available (often an unknown quantity), the pilots' taskload related to the event itself as well as to normal flying tasks, the pilots' psychophysiological state, and one or more of the following: the phase of flight during which the event occurs, the aircraft system or component involved (if any), flight parameter status, and environmental or external conditions encountered.

2.1.11 Aircraft Habitability

Aircraft habitability involves the degree to which the internal aircraft environment is fit to support human life. It involves the temperature and pressure within the aircraft, amount of oxygen, and presence of smoke or toxic fumes. Changes to aircraft habitability are typically the result of a critical event, such as an in-flight fire or a pressurization leak, and the amount of time available before crew and passengers begin to lose consciousness or perish may be quite limited.

As can be see through this discussion, many times a constraint actually reflects the inter-relationship or combination of several factors. For example, a critical event involves the condition itself, which may or may not involve a degraded status of an aircraft component, but also the phase of flight during which it occurs and how that may affect the degree to which safety might be compromised (safety risk) and the amount of time available to respond to it.

2.2 Constraint Dimensions

These 11 constraints differ relative to three different dichotomous dimensions:

- hard versus soft
- fixed versus variable
- known versus unknown

2.2.1 Hard vs. Soft Constraints

A hard constraint relates to something that must occur, such as extending the flaps in preparation for takeoff—not doing so could result in the aircraft failing to gain lift and crashing (NTSB, 1988; CIAIAC, 2008). In contrast, soft constraints pertain to actions or conditions that are desirable though are not necessarily critical and often are related to company policies, such as making an "in-range" call when cleared for an approach.

2.2.2 Fixed vs. Variable Constraints

A constraint is fixed if it delineates only one point in time when something can occur, such as responding to a microburst with windshear on final approach. Variable constraints, however, define actions that can occur within a window of time rather than at only one point (Burian et al., 2013), though the window could be relatively short as well as relatively long. Setting the takeoff flaps, for example, can actually be accomplished anytime between when ground crew are clear of the aircraft prior to push-back at the gate all the way up until the aircraft rotates on the takeoff roll (though it should be noted that it is exceedingly bad practice and dangerous to extend the flaps while the aircraft is actually on the takeoff roll). So, where during this window should a dynamic, integrated, context-sensitive information, task management and decision support system instruct or remind the crew to set the flaps? The existence of other related constraints may have some bearing on when this occurs; for example, sensors identifying slush on the taxiway might cause the system to delay the instruction to set takeoff flaps until the aircraft has arrived at the runway to eliminate the possibility of slush being thrown up and freezing on the extended flaps during taxi.

2.2.3 Known vs. Unknown Constraints

In the third dimension, known constraints are those that are understood or can be predicted; all aspects associated with the other two dimensions for a particular constraint must be understood in order for it to qualify as being "known." In other words, a known constraint is one that is understood to exist and is known to be hard or soft and fixed or variable. Unknown constraints are understood to exist but the *limits* related to that constraint are unknown. A good illustration of an unknown constraint is Time during an inflight fire event—the amount of time available to complete a safe landing and evacuation is unknown while the event is unfolding.

Therefore, developers of a dynamic, decision support tool and information and task management system will have to contend with the various constraints and their qualities relative to the three dimensions, how they are inter-related to other constraints and conditions, and determine which has priority in any given moment.

2.3 Constraint Inter-relatedness

In Table 1 and our earlier review of each of the 11 flight operations constraints and conditions, we discussed the ways in which some constraints were inter-related with each other; indeed, few constraints ever exist in isolation. Although instructive in the abstract, it can be helpful to explore even a simplified use case to further our understanding of just how vast the web of constraint inter-relatedness can be and how challenging the task of prioritization among inter-related constraints and conditions can be. For this purpose, let us consider the constraints and conditions associated with the most basic flight task: "flight path management—the planning, execution, and assurance of the guidance and control of aircraft trajectory and energy, in flight or on the ground" (Delta Air Lines Flight Path Management Steering Committee [FPMSC], 2015, p.1). In simplified terms, flight path management in the air and on the ground is determining where you want the aircraft to go and how it should get there, putting it there, and then ensuring that it stays there (Delta Air Lines FPMSC, 2015).

2.3.1 Constraint Inter-relation Use Case: Flight Path Management

To explore flight path management (FPM) constraint inter-relations, even in a simplified manner, we first must consider the constraints most central to FPM—in this case, they are four flight parameters: aircraft speed, heading or track, altitude, and geographic location. The next step is to add first layer constraints taken from the 11 previously identified and consider how they are connected to each of the four primary parameters, as shown in Figure 1. (For ease in viewing, not all the interconnections are depicted.)

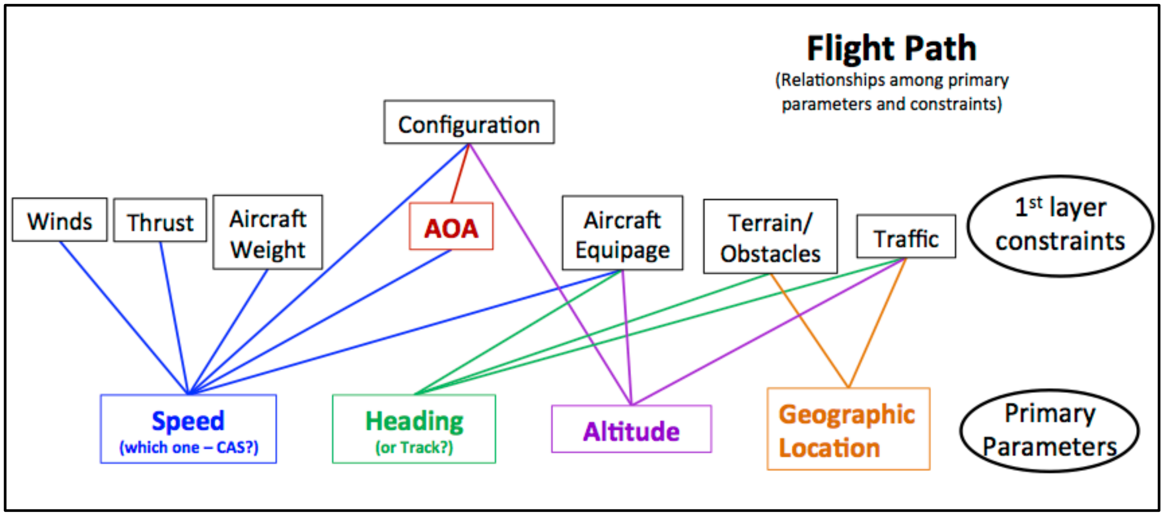

Figure 1. FPM primary parameters and first layer constraints.

First layer constraints in Figure 1 are those we believe to be most closely associated or inter-related with the first four—the four flight parameters—and they are external environmental and external conditions (wind, terrain/obstacles, traffic), aircraft system and component status (thrust, weight, configuration, angle of attack [AOA]), and aircraft equipage and maintenance status (equipage), and includes such things as the aircraft's flight management (FMS) and autoflight systems.

Second layer constraints—those that are highly associated but less so than first layer constraints—can then be considered and are included in Figure 2. For the purposes of this use case exploration, all of the second layer constraints we have selected pertain to limitations and performance expectations codified in federal aviation regulation and practical test and airman certification standards, procedures (both published and company), and company policies. In Figure 3, we have added a few additional lines (in black) to illustrate some of the inter-relationships that exist between and among first and second layer constraints, not just with the four primary flight parameters. These additional inter-relations must also be considered.

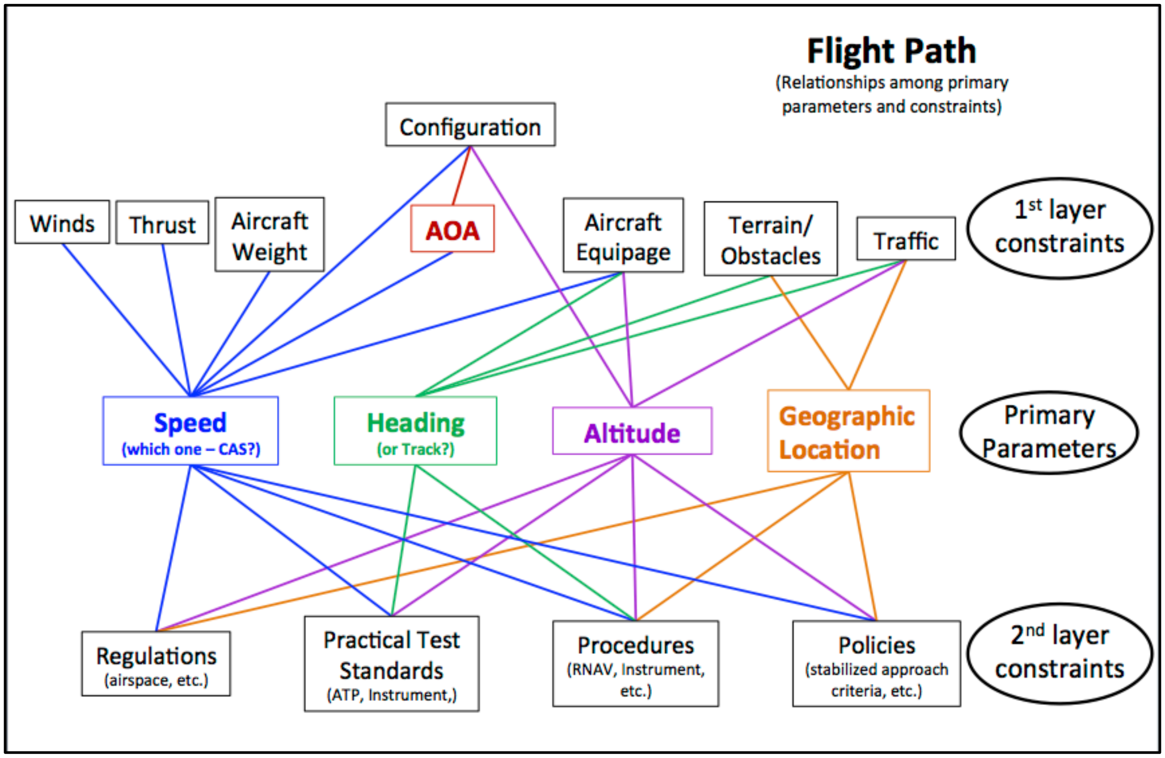

Figure 2. FPM primary parameters and first and second layer constraints.

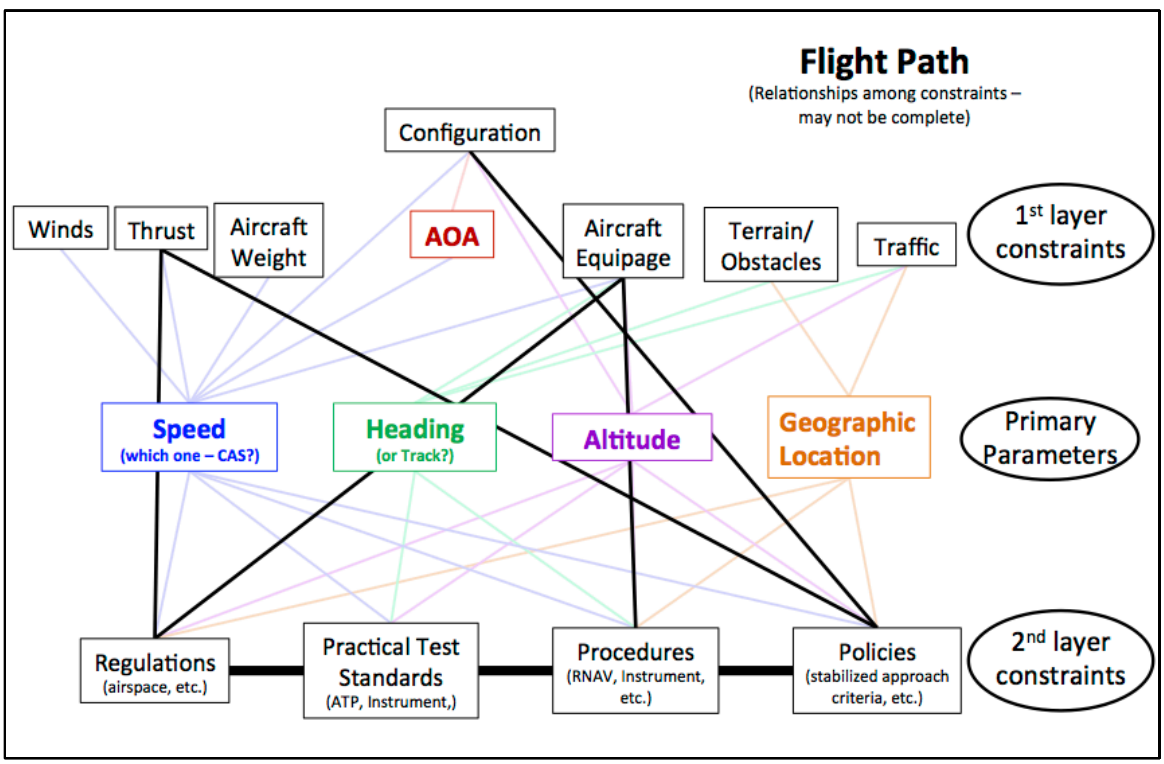

Figure 3. Some inter-relations between second layer constraints and among second and first layer constraints.

Readers should note that a large number of constraints have not yet been added to the figure for consideration. For example, phase of flight certainly has a connection to many of the FPM constraints identified (e.g., aircraft configuration, traffic, terrain regulations, procedures), as do the levels and types of risks that exist, the amount of time available, pilot workload and physiological state (e.g., fatigue), and the presence of any type of non-normal condition or emergency (i.e., a critical event). Because FPM is one of the most basic and critical of all flight operations tasks, we believe that developers of dynamic, information and flight management and decision support tools would do well to start with this task when considering constraints and conditions and how they are inter-related and how information and tasks associated with them should be prioritized in different contexts.

The second major topic covered in this report pertains to the specific data and information to be accessed, monitored, integrated, and displayed in an integrated, dynamic, information and task management and decision support tool. We turn to this topic now.

3. Data, Information, and Sources

One of the authors (Kochan) took on the herculean task of identifying much of the data and information—and where it comes from (i.e., sources)—that could be integrated and automatically presented or made available on request by a dynamic, information and task management and decision support tool (see Appendix A). The task was to not only identify but also to categorize, define, and otherwise characterize the full range of data and information for inclusion in the system. The only rule we developed prior to this undertaking was that the data and information identified should be at the smallest discrete but coherent and interpretable unit possible. For example, an altitude of “FL 210” is one discrete, but smallest interpretable unit: “FL” alone is not specific enough (it denotes any flight level [FL] at or above 18,000 ft. mean sea level [MSL]), and “210” alone could refer to a heading, a flight number, or any number of other things (e.g., the first officer’s weight, the number of passengers on board, etc.); similarly “F” or “2” or “0” by themselves are meaningless. Thus, relative to presenting altitude information in terms of feet (as opposed to hectopascals or meters), numbers are required representing feet and some other indicator (e.g., ft., FL) to distinguish feet measurement above ground level (AGL) or MSL. We call these small, discrete data and information units “information atoms” or iAtoms. As described later, time and other resource limitations precluded our ability to identify all the iAtoms in some data/information categories.

3.1 iAtom Identification

A number of documents were consulted to generate the list of iAtoms. The first was the Air Transport Association (ATA) Specification 100 (ATA, 1999) and its revision, the iSpec 2200 Information Standards for Aviation Maintenance (Airlines 4 America, 2016) published by Airlines for America (A4A), the successor to the ATA. Online master MELs for several transport category aircraft were also reviewed (see http://fsims.faa.gov/PICResults.aspx?mode=Publication&doctype=MMEL). These sources were particularly helpful in identifying iAtoms associated with aircraft structures and systems (things of greatest concern to maintenance personnel) but did not include a wide array of other data and information needed by pilots such as alerts, checklist items, or environmental/meteorological conditions.

Current flight regulations and advisory guidance from the Radio Technical Commission for Aeronautics (RTCA), Federal Aviation Administration (FAA) Advisory Circulars, and selected Aircraft Flight Manuals (see Appendix B) were consulted to identify other types of data and information, particularly those that are incorporated into current flight deck displays. With an eye to the future, NextGen Portfolios and Operational Improvements (Bolton, Bristol, & Hickey, 2014) were also reviewed and iAtoms necessary for NextGen technologies and operations were identified. iAtoms from these NextGen documents relate in large part to meteorological/environmental conditions and to communication, navigation and surveillance.

Normal checklists, quick reference handbooks (QRHs), and systems and training manuals for a number of aircraft types from different manufacturers were also reviewed. A literature review was also conducted, which yielded a few previously identified sets of flight deck data and information (Bailey et al., 2011; FAA, 2013; FAA Flight Standards Service, 2008; Schvaneveldt, Beringer, Lamonica, Tucker, & Nance, 2000). Finally, Dr. Kochan used her personal experience as a transport category aircraft pilot, airframe and powerplant mechanic (A&P) with inspection authorization (IA), and FAA designated pilot examiner, to add to the list of identified iAtoms.

3.2 iAtom Categorization and Description

Identified iAtoms were sorted and organized into the 10 functional groups listed in Table 2.

Table 2. iAtom Functional Groups

Functional Group	*Description*	*Examples of iAtoms*
Aircraft structure and systems	Basic aircraft structure, furnishings, and systems data and information	Engine ignition control position
Aircraft flight deck	Data and information found on the flight deck used in operation of aircraft and control of flight path	True airspeed
Communication, navigation, and surveillance	Data and information associated with communication, navigation, and surveillance	ILS glidepath indication
External environment	External factors such as airport design, terrain, obstacles, weather, and other meteorological phenomena	Winds aloft (at a particular altitude)
Alerts, warnings, and errors	Compilation of most common alerts, warnings, and errors (such as missing information)	Windshear alert (aural)
Documents, documentation, and procedures	Documents and reference material such as aircraft manuals, performance tables, handbooks, and checklists	Engine start procedure
Personnel: flight and cabin crew, maintenance and ground personnel	Physiological, cognitive, psychological, social interactions, and workload of on-board and on-ground crew members and personnel	Time elapsed since last rest period
Aircraft cabin and cargo compartment	Data and information associated with cabin equipment, cargo, and luggage (checked and carry on)	Galley and lavatory water quantity
Maintenance	Data and information pertaining to the maintenance of the aircraft or associated equipment	Status of compliance with airworthiness directive XX
Ground and servicing	Items associated with ground operations and servicing of the aircraft	Number of cans of orange juice on board

Because of time and resource limitations, we focused on identifying iAtoms for the following functional groups: Aircraft Structure and Systems; Aircraft Flight Deck; Communication, Navigation, and Surveillance; External Environment; Alerts, Warnings, and Errors; and Documents, Documentation, and Procedures. Additionally, and again because of resource limitations, only major types of documents and documentation that exist (e.g., non-normal checklists, minimum equipment list) were identified and included in the Documents, Documentation and Procedures functional group, rather than all the iAtoms that exist within those documents and procedures. A color-coded tab was created for each of the 10 functional groups in a Microsoft Excel™ workbook (see Appendix A).

In the five functional groups in which specific iAtoms were identified (all groups listed above except for the Documents, Documentation, and Procedures group), the iAtoms were organized, defined, and characterized relative to the fields in Table 3.

Table 3. iAtom Organization, Definition, and Characteristics

Column Heading	*Description*	*Example**	*Relevance for System Development*
Super category	A major overarching category based on root ATA codes or other categorization scheme such as checklists or Quick Reference Handbooks	Electrical	Facilitates understanding of dynamic, integrated information system architecture
Category (ATA code, if available)	A category of information sources under a Super Category; may have an associated ATA code or sub-code	Electrical power (24)	Facilitates understanding of dynamic, integrated information system architecture
Sub-category (ATA sub-code, if available)	A system, component, or procedure specific data or information source	Generator drive (24-10)	Facilitates understanding of dynamic, integrated information system architecture
iAtom	A small, discrete but meaningful unit of information or data for integration, use, and/or presentation	Generator drive indication	Information/data for display or use by the system
iAtom definition/ features	Description of the iAtom	Indication of mechanical devices that drive the generators at a desired RPM**	Facilitates understanding of iAtom and its use in the system
Units	iAtom unit of measurement (if applicable)	Not applicable	Necessary for use by the system
Static/dynamic	Whether the iAtom is static (not expected to be changing in real-time) or dynamic (changing in real-time)	Dynamic	Necessary for system to be considered a decision support tool and to provide support at appropriate level
Current source	System, computer, facility, or person providing source of data or information	Electrical system	Where iAtoms will come from for integration into system
Current location of information/data	Current location of the iAtom (e.g., specific cockpit display or document source)	Varies: typically EICAS, ECAM or similar display	Facilitates understanding of how iAtoms are currently used
Warnings/cautions/ alerts	Any existing warning or alertinf information associated with the iAtom	Generator drive	System developer awareness
Available guidance/ regulatioins	Associated regulatory and advisory guidance materials (14 CFR, RTCA, Advisory Circulars, etc.)	14 CFR 23 14 CFR 25 electrical systems and equipment	Additional sources of information relative to iAtoms, their use, and their presentation or display
Needed guidance	New regulations or guidance needed for the system	Not applicable	Gaps in needed guidance material or regulations

* Example taken from the Aircraft Structures and Systems functional group.
** RPM (revolutions per minute).

During system development, additional considerations of iAtoms will also be necessary, such as:

- *Presentation style:* iAtom "pushed" only when relevant, iAtom information to be made available only when requested by pilot (Cybenko & Brewington, 1999), or iAtom is constantly presented
- *Modality and location:* visual, aural, haptic, localization, display unit on which it appears, location on display unit, etc.
- *Correspondence:* iAtom always or often presented with what other iAtoms and under what conditions
- *Features:* text/alphanumeric, graphic, picture, color, 2D, 3D, volume, aural sound/spoken language, font size, bolded, flashing, etc.
- *Thresholds:* conditions, situations and parameter values that trigger iAtom presentation
- *Source:* new sources for iAtom availability, if different from current sources
- *Verification criteria (dynamic iAtoms only):* criteria which must be met to ensure that dynamic iAtom data and information from sources is up-to-date and accurate
- *Priority weighting:* weighting score given to iAtom to be used for making prioritization decisions regarding presentation of iAtoms relative to others

3.3 iAtom Relationship to Contextual Constraints

Earlier we considered the FPM use case to illustrate inter-relationship among different types of constraints. We began by identifying the primary constraints most closely related to FPM: aircraft speed, heading or track, altitude, and geographic location. Recall that constraints are actually thresholds or limits that exist. For example, imagine that we are in an aircraft that is flying at flight level 360 (36,000 feet, MSL). The winds that we encounter at that altitude (i.e., winds aloft), both their speed and direction relative to our track, will affect the speed with which our aircraft travels over the ground. If the winds are coming directly against us (a direct head wind) and they are strong, they will constrain or limit our forward speed more than if they are light. If the winds aloft are instead a tailwind for us (i.e., push us from behind), they are not a constraint at all on our forward speed, and actually can help us arrive at our destination earlier.

The value of the winds aloft speed that we encounter (e.g., 45 knots), by itself, is just information: an iAtom. But when considered relative to our aircraft, and our goal to get from one place to another, that wind now possibly becomes a constraint. Just how constraining or limiting depends upon the strength of the wind (the iAtom value of the wind), but also its direction relative to our aircraft and also other factors such as how much thrust our aircraft is producing, our aircraft's weight, and a variety of other related factors, such as how aerodynamic the design of our aircraft is for that altitude. Thus, one or more iAtoms is associated with each constraint or condition depending on current flight operation goals and associated tasks.

Table 4 shows several iAtoms (taken from Appendix A) that are related to the FPM geographic location parameter constraint; at any point in time one or more might be needed for display by a dynamic, integrated, flight information and automation management system.

Table 4. iAtom Associated with Geographic Location

Super Category	*Category (ATA Code, if available)*	*Sub-Category (ATA Sub-Code, if available)*	*iAtom*
Surveillance	Location	Altitude	Altitude
Surveillance	Location	Satellite referenced	Latitude/longitude
Surveillance	Location	Navaid referenced	VOR radial/distance
Surveillance	Location	Radar referenced	Map icon (radar)
Surveillance	Location	Landmark referenced	Direction/DME from landmark
Surveillance	Location	Point-in-space referenced	Map icon (4D trajectory)

This is just a small sample of the iAtoms that might be presented relative to just one constraint associated with FPM tasks. Consider just how many other iAtoms that also need to be conveyed at a single point in time associated with all the other pilot tasks and constraints that exist then!

The development and design process for autonomous, integrated context-sensitive, task management and decision support tools is tremendously complex and is most easily accomplished if considered in sections and by constraint type, such as by phase of flight, suggested earlier. Airlines participating in the Advanced Qualification Program (AQP) have already completed detailed task analyses for their flight operations (e.g., Lanzano, Seamster, & Edens, 1997) and aviation researchers have done the same for various studies (e.g., Burian et al., 2013; Hooey, Foyle, & Andre, 1997). After system developers have built on and extended existing task analyses by phase of flight, they should identify iAtoms associated with those tasks for incorporation into the system (see for example, Schvaneveldt, Beringer, & Lamonica, 2001). In parallel, developers must also identify the constraints and conditions associated with and impinging upon the completion of the tasks identified. With tasks, iAtoms, and constraints and conditions identified, developers can then begin the process of designing the system and displays in keeping with the role the system is expected to play and how it is to function and behave (Mosier et al., 2017).

4. Conclusion

In the companion report to this document (Mosier et al., 2017), we made the case that autonomous, context-sensitive, task management and decision support tools hold great promise for supporting increasingly complex operations in aviation and other high-risk, dynamic, socio-technical work domains. We described some of the many issues that will need to be addressed during the first stage of developing these systems. These issues center on the role that the system is to have relative to human operators and how it should function to most effectively fulfill that role.

In this report we explored in more depth the contextual constraints that will drive the dynamic behavior of such systems and the types of data and information that will be sensed, collected, integrated and displayed on the flight deck. These are two critical initial steps in the development of these systems following conception and functional requirement definition. It is likely that by considering the contextual constraints within specific operational contexts and identifying and prioritizing the data and information needed, developers will find themselves engaging in an iterative process whereby constraints, data and information, and system functionality and role will be further defined with increasing specificity.

Thus, these reports serve as the foundation—but only the beginning—in understanding and approaching the development and design of these highly complex but extremely powerful systems.

5. References

Abbott, K. A., McKenney, D., & Railsback, P. (2013). Operational use of flight path management systems–Final report of the Performance-based operations Aviation Rulemaking Committee. *Commercial Aviation Safety Team Flight Deck Automation Working Group*.

Abbott, T. S., Jones, K. M., Consiglio, M. C., Williams, D. M., & Adams, C. A. (2004). *Small aircraft transportation system, higher volume operations concept: Normal operations*. (NASA/TM-2004-213022.) Hampton, VA: NASA Langley Research Center

Airlines 4 America. (2016). *iSpec 2200: Information standards for aviation maintenance 2016.1*. Washington, DC: A4A Publications.

Bailey, R. E., Prinzel, L. J., Kramer, L. J., & Young, S. D. (2011). *Concept of operations for integrated intelligent flight deck displays and decision support technologies*. (NASA/TM-2011-217181.) Hampton, VA: NASA Langley Research Center.

Banks, S. B., & Lizza, C. S. 1991, Pilot's associate: a cooperative, knowledge-based system application. *IEEE Expert, 6,* 18 – 29.

Berman, B. A., Kochan, J. A., Burian, B. K., Pruchnicki, S., Christopher, B., & Silverman, E. (2017). Alerts and cues on the flight deck: Analysis and application in training. *NASA Technical Memorandum*. Moffett Field, CA.: NASA Ames Research Center.

Bolton, E. L., Bristol, T., & Hickey, J. J. (2014). *NextGen priorities joint implementation plan: Executive report to Congress*. Federal Aviation Administration. Washington, DC.

Burian, B. K., Barshi, I., & Dismukes, K. (2005). The challenge of emergency and abnormal situations. *NASA Technical Memorandum, (*NASA/TM 2005-213462). Moffett Field, CA: NASA Ames Research Center.

Burian, B. K., Christopher, B., Fry, D., Pruchnicki, S., & Silverman, E. (2013). Jet single-pilot simulation study scenario overviews, task analyses, and concurrent task timelines. *NASA Technical Memorandum, (*NASA/TM-2013-216608). Moffett Field, CA.: NASA Ames Research Center.

Burian, B.K., & Martin, L. (2011). Operating documents that change in real-time: Dynamic documents and user performance support. In Guy Boy (Ed.), *The handbook of human-machine interaction: A human-centered design approach*, pp. 107-130. Surrey, England: Ashgate.

Burian, B. K., Mosier, K. L., Fischer, U. M., Kochan, J. A. (in press). New teams on the flight deck: Humans and context-sensitive information automation. In E. Salas & F. Jentsch (Eds.) *Human* *factors in aviation* (3rd ed.). New York: Academic Press.

Champigneux, G. (1995). In AGARD Lecture Series 200: *Knowledge-based functions in aerospace systems* (pp. 5-1 – 5-10). Neuilly-Sur-Seine, France.

Comision de Investigacion de Accidentes e Incidentes de Aviacion Civil [CIAIAC]. (2008). *Accident involving a McDonnell Douglas DC-9-82 (MD-82) aircraft, registration EC-HFP operated by Spanair, at Madrid-Barajas Airport, on 20 August 2008* (Report A-032/2008). Retrieved from http://www.fomento.es/NR/rdonlyres/EC47A855-B098-409E-B4C8-9A6DD0D0969F/107087/2008_032_A_ENG.pdf

Cybenko, G., & Brewington, B. (1999). The foundations of information push and pull. *The mathematics of information coding, extraction and distribution* (pp. 9-30). New York: Springer.

Degani, A., & Wiener, E. L. (1994). Philosophy, policies, procedures, and practices: The Four "P"s of flight deck operations. In N. Johnston, N. McDonald, and R. Fuller (Eds.), *Aviation psychology in practice* (pp. 44-67). Hants, England: Avebury Technical.

Delta Air Lines Flight Path Management Steering Committee. (2015). *Delta Air Lines Flight Path Management Steering Committee Report: Recommendations to Improve Flight Path Management*. Internal Technical Report: Delta Air Lines.

Durso, F. T., & Sethumadhavan, A. (2008). Situation awareness: Understanding dynamic environments. *Human Factors, 50*(3), 442-448.

Endsley, M. R. (2000). Theoretical underpinnings of situational awareness: A critical review. In M. R. Endsley & D. J. Garland (Eds.), *Situation awareness, analysis, and measurement* (pp. 317-341). Mahwah, NJ: Erlbaum.

Estes, S. L., Burns, K. J., Helleberg, J. R., Long, K. M., Pollack, M. E., & Stein, J. L. (2016, November). Digital copilot: Cognitive assistance for pilots. *Proceedings of the AAAI Fall Symposium Series*. Arlington, VA.

FAA Flight Standards Service. (2008). Federal Aviation Administration Joint Aircraft System/Component Code Table and Definitions. October 27, 2008, Regulatory Support Division, Aviation Data Systems Branch, AFS-620, Oklahoma City, OK, retrieved from http://av-info.faa.gov/sdrx/documents/JASC_Code.pdf

Fischer, U., Orasanu, J., & Davison, J. (2003). Why do pilots take risks? Some insights from a think-aloud study. In M. J. Cook (Ed.), *Proceedings of the Human Factors of Decision Making in Complex Systems Meeting* (pp. 44-46). Dundee, Scotland: University of Abertay.

Hooey, B. L., Foyle, D. C. & Andre, A. D. (2000). Integration of Cockpit Displays for Surface Operations: The final stage of a human-centered design approach. *SAE Transactions: Journal of Aerospace*, 109, 1053-1065.

Lanzano, J., Seamster, T., & Edens, E. (1997). The importance of CRM skills in an AQP. In R. Jensen (Ed.), *Proceedings of the 9th Symposium of Aviation Psychology* (pp. 574–579). Columbus, OH: Ohio State University

Letsu-Dake, E., Rogers, W., Whitlow, S. D., Nelson, E., Dillard, M., Dorneich, M. C., & Dudley, R. (2015, September). Flight deck information automation: A human-in-the loop in-trail procedure simulation study. In *Digital Avionics Systems Conference (DASC), 2015 IEEE/AIAA 34th* (pp. 3D1-1). IEEE.

Matheus, C. J., Kokar, M. M., Baclawski, K., Letkowski, J. J., Call, C., Hinman, M., & Boulware, D. (2005). *Lessons learned from developing SAWA: A situation awareness assistant*. (Technical report). Rome, NY: Air Force Research Laboratory.

Miller, C. A. & Hannen, M. D. (1999). The rotorcraft pilot's associate: Design and evaluation of an intelligent user interface for cockpit information management. *Knowledge-Based Systems*, *12*, 443 – 456.

Mosier, K., Fischer, U., Burian, B. K., & Kochan, J. (2017). Autonomous, context-sensitive, task management systems and decision support tools I: Human-autonomy teaming fundamentals and state of the art. *NASA Technical Memorandum*, Moffett Field, CA: NASA Ames Research Center.

Mosier, K., & Skitka, L. (1996). Human decision makers and automated decision aids: Made for each other? In R. Parasuraman & M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp 201-220). Mahwah, NJ: Lawrence Erlbaum Associates.

National Transportation Safety Board [NTSB]. (1988). *Northwest Airlines, Inc., McDonnell Douglas DC-9-82, N312RC, Detroit Metropolitan Wayne County Airport, Romulus, Michigan, August 16, 1987*. Aircraft Accident Report (NTSB/AAR-88/05). Washington, DC: National Transportation Safety Board.

Orasanu, J., Fischer, U. & Davison, J. (2004). Risk perception and risk management in aviation. In R. Dietrich and K. Jochum (eds.), *Teaming up: Components of safety under high risk* (pp. 93-116). Aldershot, UK: Ashgate.

Sarter, N. B., Woods, D. D., & Billings, C. (1997). Automation surprises. In G. Savendy (Ed.), *Handbook of human factors/ergonomics* (2nd ed., pp. 1926-1943). New York: Wiley.

Schvaneveldt, R. W., Beringer, D. B. & Lamonica, J. A. (2001). Priority and organization of information accessed by pilots in various phases of flight. *International Journal of Aviation Psychology, 11*(3), 253-280

Schvaneveldt, R., Beringer, D. B., Lamonica, J., Tucker, R., & Nance, C. (2000). Priorities, Organization, and Sources of Information Accessed by Pilots in Various Phases of Flight (DOT/FAA/AM-00/26), Office of Aviation Medicine, Washington, DC. Retrieved from https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2000s/media/00_26.pdf

Appendix A. Information Sources and iAtoms

Here is the link to the iAtom spreadsheet:

https://hsi.arc.nasa.gov/flightcognition/Publications/FAIMTM2_AppA_iAtoms.xlsx

Appendix B. iAtoms Reference Documents

The following documents were used in the creation of the iAtoms listing.

Document	Document Description	Date
14 CFR 25	Airworthiness Standards: Transport Category Airplanes	02/17/2017
14 CFR 25.771	Pilot compartment	02/17/2017
14 CFR 25.777	Cockpit controls	02/17/2017
14 CFR 25.1302	Installed systems and equipment for use by the flightcrew	02/17/2017
14 CFR 25.1303	Flight and navigation instruments	02/17/2017
14 CFR 25.1309	Equipment, systems, and installations	02/17/2017
14 CFR 25.1321	Arrangement and visibility	02/17/2017
14 CFR 25.1322	Flightcrew Alerting	02/17/2017
14 CFR 25.1329	Flight guidance system	02/17/2017
14 CFR 25.1333	Instrument systems	02/17/2017
AC 20- 131A[1]	Airworthiness Approval of Traffic Alert and Collision Avoidance Systems (TCAS II) and Mode S Transponders	03/29/1993
AC 20-138D[1]	Airworthiness Approval of Positioning and Navigation Systems	03/28/2014
AC 20-151B[1]	Airworthiness Approval of Traffic Alert and Collision Avoidance Systems (TCAS II), Versions 7.0 & 7.1 and Associated Mode S Transponders	03/18/2014
AC 20-175[1]	Controls for Flight Deck Systems	12/08/2011
AC 25-11B[1]	Electronic Flight Deck Displays	10/07/2014
AC 25.1302-1[1]	Installed Systems and Equipment for Use by the Flightcrew	05/03/2013
AC 25.1309-1A[1]	System Design and Analysis	06/21/1988
AC 25.1322-1[1]	Flightcrew Alerting	12/13/2010
AC 25.1329-1C[1]	Approval of Flight Guidance Systems	10/27/2014
AC 90-100A[1]	U.S. Terminal and En Route Area Navigation (RNAV) Operations	03/01/2007
AC 90-105A[1]	Approval Guidance for RNP Operations and Barometric Vertical Navigation in the U.S. National Airspace System	03/07/2016
AC 120-109A[1]	Stall and Stick Pusher Training	11/24/2015
Boeing 737 NG	Flight Manual	06/15/2012
Boeing 737 NG	Operating Manual Volume 1	04/07/2009
Boeing 777	Flight Manual	10/28/2011
Boeing 777	Operating Manual Volume 2	06/27/2012
DOT/FAA/TC/44 DOT-VNTSC-FAA-13-09	Human factors considerations in the design and evaluation of flight deck displays and controls, Version 1.0.	November 2013
FAA Human Factors Team Report	The Interfaces Between Flightcrews and Modern Flight Deck Systems	06/18/1996
FAA DTFAWA-10-E-00030	FAA, (2013). Aircraft Access to System-Wide Information Management (AAtS) Concept of Operations.. Booz, Allen Hamilton, McLean, VA.	2013
iSpec 2200	Airlines 4 America (2016). *iSpec 2200: Information Standards for Aviation Maintenance 2016.1.* Washington, DC: A4A Publications.	2014.1

Document	Document Description	Date
	https://publications.airlines.org/CommerceHomepage.aspx	
PS-ANM25-16[2]	Low-Speed Alerting and/or Protection	Proposed
RTCA DO-318	Safety, Performance and Interoperability Requirements Document for Enhanced Air Traffic Services in Radar-Controlled Areas Using ADS-B Surveillance (ADS-B-RAD)	09/09/2009
RTCA DO-348	Safety, Performance and Interoperability Requirements Document for Traffic Situation Awareness with Alerts (TSAA)	03/18/2014
RTCA DO-360	Standards Development Activities for using Near Real-Time Aircraft-Derived Data in Future Applications	09/22/2015

[1] FAA Advisory Circulars (AC), [2] FAA Policy Statement Number (PS)