Proposition of an ontology supporting context modeling in operational scenario development

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Air Traffic Control systems are complex sociotechnical systems which do not comprise solely technical elements, but also have human and organizational dimensions. Recent approaches to Systems Engineering, and in particular Human Systems Integration, are placing increasing emphasis on incorporating these non-technical considerations into the design processes of complex sociotechnical systems. In particular, one crucial aspect in design is to understand the operational context of the system. There is a lack of tools and languages expressive enough to include contextual information into system models. This is especially true for the Air Traffic Control field, as the operational context of a control tower and the tower itself are deeply intertwined and interdependent. This paper is a step towards the achievement of better integration of context-related knowledge into system design processes. We conducted a case study analysis based on a literature review and feedback from civilian and military air traffic control practitioners, and we propose an ontology of the contextual elements that characterize the context of air traffic control operations.

Keywords— Contextual Modeling, Human Systems Integration, Sociotechnical Systems, Ontology, Air Traffic Control Operations

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I. Introduction

The sociotechnical nature of Air Traffic Control (ATC) systems makes them challenging to design. Balancing the technical requirements with the social, organizational and human factors is complex. Dynamic and unpredictable environments make it difficult to anticipate how such systems will behave. What makes Sociotechnical Systems (STSs) difficult to design is the fact that their behavior can only be observed once the system has been integrated and put into operation. Only then do the so-called emergent properties of the system arise and highlight the architecture and design flaws which could hardly be anticipated at design time. In other words, there is a shift between the tasks that were prescribed by designers and the actual activity of the resulting STS [1]. Human Systems Integration (HSI) is an academic and industrial effort that strives to better integrate these non-technical considerations throughout the entire lifecycle of complex STSs.

The discrepancies between tasks (the designed procedures) and activity (what is effectively done when the system is operating) are mostly due to the fact that the *operational context* of the system (i.e., the context of the system at operation time) is different from the context of the system as it was considered at design time. The notion of context is key here, and the literature in Systems Engineering (SE) and HSI acknowledges the fundamental nature of context in our understanding of complex systems [2, 3]. However, the same literature lacks both theoretical and practical foundation as to what the context of a system is, how it interacts with the system, and how it can be captured in system models.

In a previous work, we proposed a general definition and characterization of the operational context of complex STSs [4]. In this paper, we build upon this preliminary work and take a step forward by proposing an ontology of contextual elements tailored to the ATC domain. We adopt a research methodology based on the ontology construction guidelines form Pinto [5]. We used principles of Case Study Analysis [6] to collect data, including feedback from experienced Air Traffic Controllers (ATCos), regulatory documents and academic papers. Our main research objective is to identify the contextual elements that are relevant to the operations of military and civilian control towers, and to analyze them in order to propose an ontology of concepts that characterize the context of such systems.

The remainder of the paper is structured as follows. Section II presents related work on context definition and characterization from an HSI perspective. Section III discusses the adopted research methodology. Section IV presents the construction process of the ontology. Section V discusses the ontology evaluation process. Section VI provides a short discussion on the implications and limitations of our work. Section VII concludes the paper.

II. Background and related work

An ATC system is an instructive example of a complex sociotechnical system in the sense that there is an intricate interplay between various technological, organizational and human components during operations. The tryptic *Technology*, *Organizational* and *People* is important and is referred to as the TOP model in the HSI literature [7]. HSI is a transcdisciplinary approach which advocates for the extensive use of modeling and simulation to acquire as

much knowledge as possible about a system before this system comes into operation. One objective of HSI-driven methodologies is to capture and understand emergent properties of a system even before the system has been delivered and operated. This way designers still have the time and resources to identify the flaws in the system and fix its design accordingly.

What makes a system behave differently when it is operating, compared to when it was being designed, is that the *context* of the system is different at each stage of the system lifecycle, from initial concept to final retirement. However, context is an essentially contested concept with multiple definitions across different fields [4]. The context framework proposed in [4] consists of a definition (what context is) and a characterization (what context is made of) from an HSI and STS design perspective. The overall representation of this framework is illustrated in Figure 1.
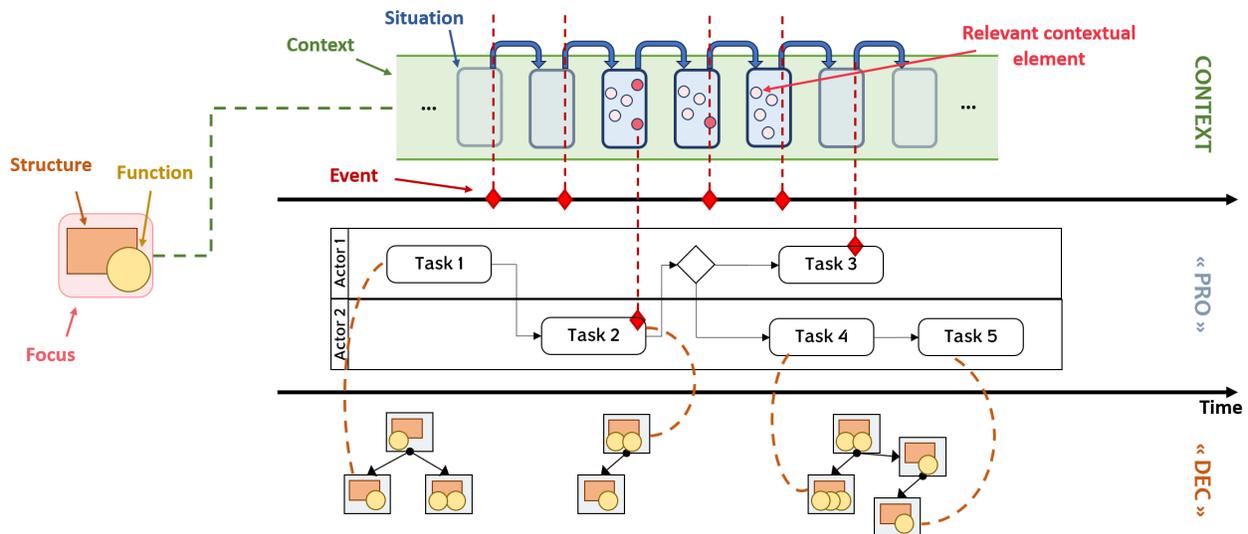
Fig. 1   The framework for the operational context of a system (*taken from [4]*)

The main idea of this framework is that context is relative to a *focus*, i.e., to a specific part of a system (the structure) carrying out a specific function. For instance, when a tower controller (the structure) supervises the landing of a plane on the track (its function), there are contextual elements (e.g., weather) that may influence its behavior and the outcome of the function. Our framework emphasizes the idea that context *changes* through time. Hence it is *dynamic*. As time goes forward, events occur and may make contextual elements evolve (e.g., weather may change). Some contextual elements may become relevant to a given focus while other may become irrelevant, thereby creating a sequence of different *situations*. Finally, the framework highlights the close interdependence between context (the top layer in Figure 1) and the behavior and architecture of the system (the middle and bottom layers, which represent respectively the *procedural* knowledge (what the system does) and the *declarative* knowledge (what the system is made of)).

The main limitation of this framework is that it is only a macroscopic view of how a system interrelates with its operational context. The contextual elements have not been properly defined and characterized. To do so, we propose to

define an ontology that will support the characterization and the relationships of the contextual elements. The case study of ATC operations is particularly adapted, as it provides instructive examples of complex sociotechnical operations having a strong dependence on their operational context.

III. Research methodology

The objective of this research is to construct an ontology that characterizes the operational context of complex STSs in order to inform SE and HSI processes and system modeling. In ontology engineering, it is often easier to first develop a *domain ontology* [5], which is an ontology specific to a domain, and then try to generalize it to other applications (this is a *bottom-up* construction approach [8]). An ATC case study is used for ontology development and case study approach. Figure 2 synthesizes the overall research methodology that we will detail in this section.
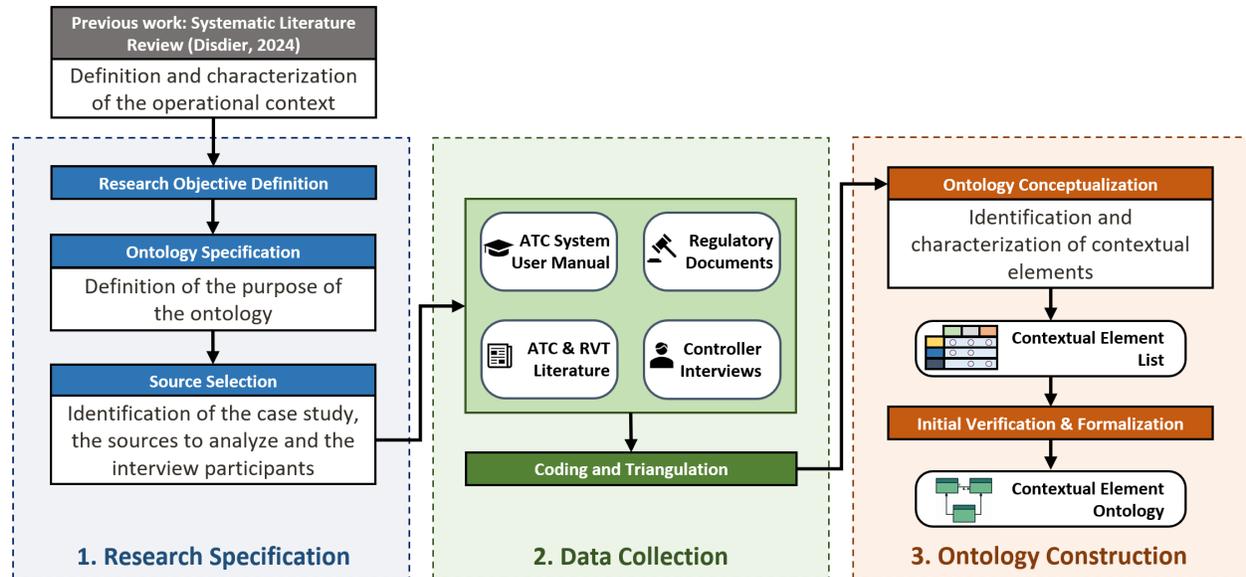
Fig. 2   Overview of the research methodology, adapted from [5]

In philosophy, the word "*ontology*" refers to a systemic explanation of being. More precisely, [9] defines an ontology as something that "*defines the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extensions to the vocabulary*". As [10] points out, even though most researchers agree on the definitions of an ontology, there is not one single approach to ontology building as each development team and each domain has its own set of principles, criteria and rules. Nevertheless, [11] draws the following list of the most common goals of an ontology:

1) To share common understanding of the structure of information among people or agents;
2) To enable reuse of domain knowledge (that is, to build larger ontologies based on other smaller ontologies);
3) To make explicit assumptions about a domain and its terms;
4) To separate the domain knowledge from the operational knowledge (that is, to separate structural information

about the concepts of domain from the way it is handled in algorithms);

5) To carry out formal analyses on domain knowledge.

[12] give multiple references on methodologies for ontology building, especially in the fields of knowledge engineering and information science. In this research, we base ourselves on the approach proposed by Pinto [5]. Pinto identifies the following processes of ontology development: *Specification, Conceptualization, Formalization, Implementation, Maintenance, Knowledge Acquisition, Evaluation and Documentation*. She adds that these processes are not necessarily meant to be conducted in sequence, but there may be loops and refinements between them. Furthermore, not all these activities need to be conducted depending on the objective of the researchers.

While the broader objective of the research is to identify the concepts and their relationships that characterize the operational context of complex STSs, the current focus is limited to the ATC domain. This approach aligns with [8], who advocate for a bottom-up methodology in ontology construction. The proposed ontology, classified as a domain ontology [5], is developed to identify the concepts and relationships relevant to the operational environment of complex STSs, with the aim of supporting SE, HSI and system modeling activities. Given that the objective is to support shared understanding rather than to implement an interoperable system, a conceptual model expressed in a semi-formal language is considered sufficient [13].

To construct the ontology, we adapt the framework from [5] and propose to conduct the following activities:

Knowledge Acquisition

Data was collected through a Case Study Analysis approach. Modern case study research draws its foundations from qualitative and constructivist research traditions across fields such as anthropology, history, psychology, and sociology [14]. Case Study Analysis guidelines used in this research were developed by [6], which advocate for the use of qualitative research techniques [15] as a data collection tool. Such techniques include observation, interviews, and analysis sessions with Subject Matter Experts (SMEs). Interviews in particular are a common and convenient data collection technique. They can be structured, semi-structured or informal. Semi-structured interviews are distinguished by precisely worded questions, yet letting the interviewer some room to adaptation of these questions depending on the answers from the participants. We conducted semi-structured, one-to-one interviews with three ATC practitioners to collect contextual information related to nominal and off-nominal operational scenarios of air traffic controllers. The three participants we interviewed have multiple decades of experience as civilian and/or military air traffic controllers, and are also involved as technical advisors in the design, development, verification and validation processes of current military air traffic control systems. The semi-structured interview protocol that we used to collect data from SMEs about contextual information in ATC procedures is detailed in Table 1.

In case study research, it is best to "*triangulate*" data from different sources [16]. Therefore, in complement to the interviews, we also extracted information about the context of ATC systems from ATC system documentation, academic

Table 1 The interview protocol

Question or remark	Expected time
Phase 1: Introduction	
[Brief description of research context and interview objectives]	5 min
[Presentation of the different phases of the interview]	
Phase 2: Warm-up	
Can you introduce yourself and briefly describe your current role in the company?	5 min
As an air traffic controller, where did you work and what was your role?	
Phase 3: High-level scenario elicitation	
Can you detail the major phases of control?	15 min
[Select a particular control phase and detail it further in the subsequent interview phases]	
Phase 4: Elicitation of contextual information for a specific phase	
Phase 4.1: Sources of information	
What are the main sources of information used by an air traffic controller?	
What are the main visual cues around the aerodrome that controllers rely on?	10 min
Are there non-visual cues used by controllers in the assessment of the situation?	
What technical systems are most needed by a controller?	
Phase 4.2: Communication, cooperation and collaboration	
Who are the other stakeholders in the control process? What tasks do they need to do?	
How do you communicate with them? What information do you need and share with them?	10 min
Which resources are needed to conduct the communication tasks?	
Can you encounter communication or understanding difficulties? Which ones?	
Phase 4.3: Human factors	
What are the most critical tasks of a controller in your opinion? Why?	
Which situations are the hardest to manage? Why?	15 min
When you are under pressure, what strategy do you adopt? Which resources are critical?	
Which contextual elements influence the situation? Do they affect the tasks or the controllers?	
Phase 4.4: Off-nominal and emergency situations	
Which tasks, actors and resources are affected in case of major technical failures?	
How context can disrupt procedures? How do you react to such disruptions?	
How sensible are control procedures to political and economical contexts?	20 min
What is the impact of weather on tasks, actors, resources and context?	
What other contextual elements might influence the procedures? How granular are they?	
Phase 5: Acknowledgements and closure	

literature and regulatory documents. We selected papers that provided feedback from ATC practitioners on how ATC operations may influence or may be influenced by their operational context. We extended our academic literature sources to papers concerned with Remote Tower Operations (RTO) [17], as they provide insight into how controllers' work is affected by their context, since the context in a remote tower may be drastically different from the context within a traditional, physical tower. Figure 3 details the research process, from the list of references we used including the profile of the participants that we interviewed, to the final list of contextual elements that we obtained in the end.
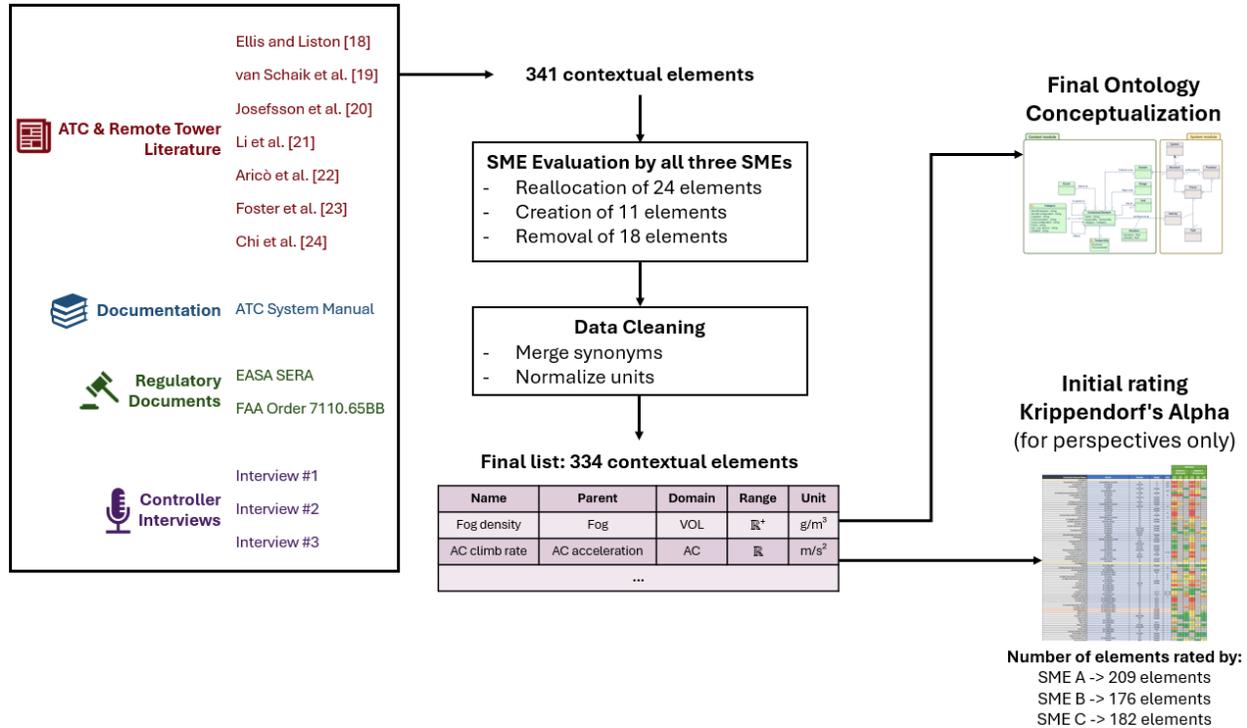
Fig. 3   Flowchart from initial data to proposed ontology

Conceptualization

In the second step, collected data was analyzed to propose a list of contextual elements relevant to ATC operations. We identify from this list the main concepts and the relationships between them. Some of these concepts describe entities having independent existence (those are the *concepts* of the ontology). The other concepts refer to the attributes of these entities (those are called the *properties* of the ontology). Finally, we identify the relationships and constraints between these concepts in terms of classes, subclasses, types and cardinality [11].

Ontology Formalization

As previously noted, the objective of this research is not to develop an ontology formally encoded in a knowledge base, using a specific representation language such as OWL. Instead, the focus is on constructing a conceptual model intended to support basic reasoning. Cranefield [18] says that in that case, the Unified Modeling Language (UML)* is a strong semi-formal modeling language candidate. Therefore, in this research, we propose to graphically model our ontology using UML.

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*https://www.uml.org (*last accessed by author in April 2025*)

Initial Evaluation

Ontology Evaluation is a process divided into Validation (does our ontology fulfill its objectives?), Verification (is our conceptualization correct according to the accepted understanding about the domain of specialized knowledge sources?) and User Assessment (is the ontology undestandable, usable and useful?) [5]. Evaluation is a fuzzy process and may occur at each phase of the ontology lifecycle. In this research, we provide a partial ontology evaluation, primarily through verification sessions. We conducted individual verification sessions with the same SMEs to assess the validity and the relevance of the contextual elements that we elicited. Their feedback helped us refine our contextual element list and hence reinforce the data upon which our ontology is built. We describe our verification protocol in more detail in Section V.

IV. Results: conceptualization and formalization of the ontology

The initial list of contextual elements contained 341 elements that were identified having an influence on ATC procedures at some point. Several evaluation iterations enabled us to refine the list to 334 contextual elements (see Figure 3). This final list of 334 contextual elements is given in the appendix.

We noticed that every contextual element could be described as a mapping from one set to another (Figure 4). For example, the *runway status code* is a contextual element that takes a runway (which belongs to the set of physical structures) and affects to it the value "*Operating*", "*Occupied*" or "*Close*". More generally, a contextual element takes an element from the mapped set (the *domain*) and associates it with an element from the mapping set (the *range*). Domains are classes of elements that can be physical structures (e.g., a radar), cognitive structures (e.g., a stripping software library), organizations (e.g., an *En-route* center) or other types of abstract entities (e.g., a restricted airspace area).

After we identified all the contextual elements with their respective domain and range, we classified them into categories. We used a qualitative clustering technique, inspired by inductive approaches such as grounded theory [19]. In grounded theory research, theories are constructing from data, without making assumptions or hypotheses beforehand. More specifically, we assigned to each contextual element a parent contextual element. Here, "*parent*" does not refer to inheritance as in object-oriented or systems modeling formalisms. Instead, we adopt a terminology used in qualitative conceptual clustering [20], in which a contextual element A is said to be a parent of contextual element B when information about B reduces uncertainty about A. The relationship therefore expresses a direction of inference rather than a direction of property propagation.

For example, SMEs reported that the observation of particular cloud types (e.g., cumulonimbus) gives them immediate operational cues about higher-level cloud conditions affecting visibility or turbulence. Hence, "cloud type" is linked as a child to the more general "cloud conditions" element. Note that the type of inference is specific → general, which is appropriate for conceptual abstraction even though it differs from more conventional inheritance-based system modeling paradigms. Finally, a category is a contextual element with no parent.
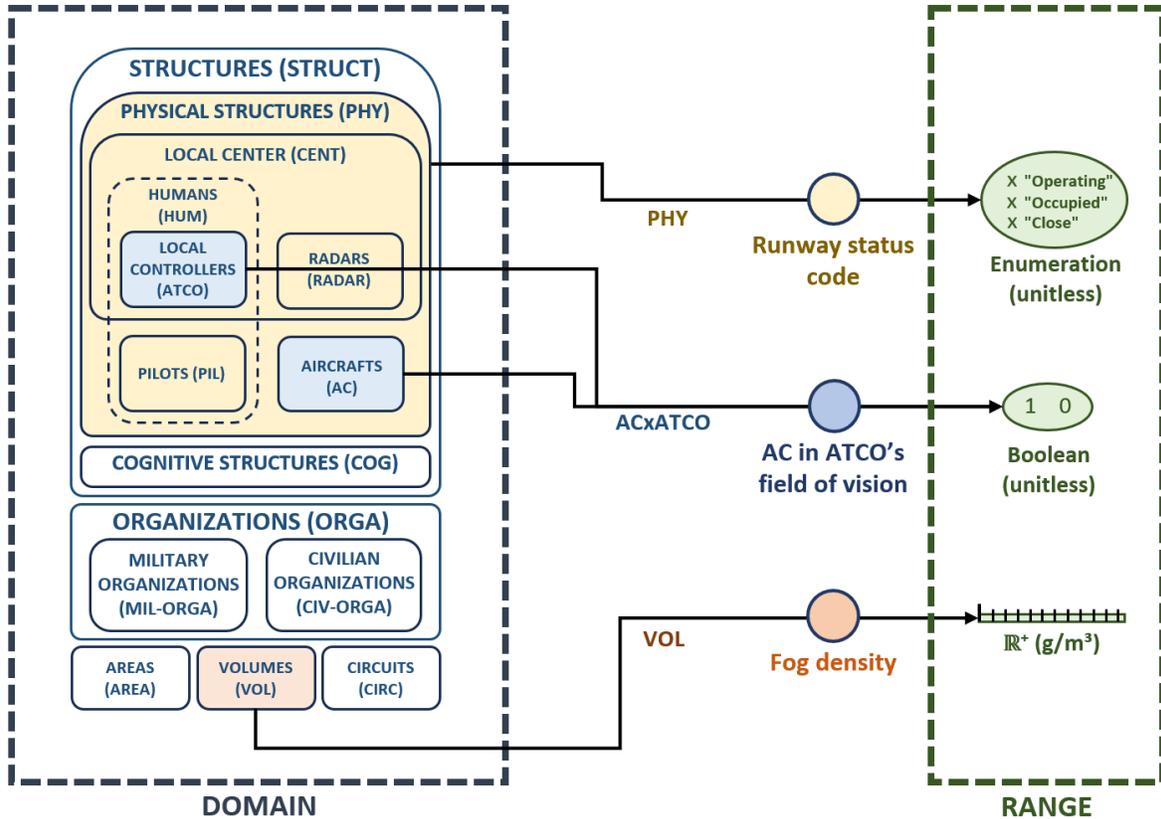
Fig. 4 Contextual elements map elements from a domain to a range

At the end of this process, and after gathering feedback from SMEs during the initial evaluation sessions (described in the next section), we obtained the eight following categories of contextual elements:

- **Weather (40 contextual elements)**: The contextual elements related to weather and environmental conditions around the local center;

- **Cognition (45 contextual elements)**: The contextual elements related to cognitive functions required in controllers' everyday activities, and their limitations;

- **Social cognitive factors (41 contextual elements)**: The contextual elements related to the controllers' social interactions, individual experiences and outside influences, as described by social cognitive theories [21];

- **Communication (29 contextual elements)**: The contextual elements related to communication between controllers and other teams, and between controllers themselves;

- **Aircraft behavior (34 contextual elements)**: The contextual elements related to the behavior of the aircrafts around the local center (this is the *procedural* knowledge that describes how the air traffic evolves around a local center);

- **Aircraft configuration (33 contextual elements)**: The contextual elements related to the state of the aircrafts around the local center (this is the *declarative* knowledge that describes the status of the aircrafts);

- **Local configuration (88 contextual elements)**: The contextual elements related to the specificities and state of the local center and its surrounding terrain;

- **Policy (24 contextual elements)**: The contextual elements related to policies at different scales and their consequences on control operations (the local center policy, the government policy, the air regulation policy, and so on).

Collected data and feedback from SMEs allowed us to identify several properties of contextual elements. Elements have intedependencies, as well as different levels of temporality and criticality. Figure 5 illustrates examples of these properties for 16 contextual elements. There exist interdependencies between contextual elements, as the state of a contextual element at a given time may affect the state of another contextual element. These interdependencies define cause-and-effect phenomena which lead to the emergent properties of the system. The temporality refers to the persistence of a contextual element. Contextual elements can range from circumstancial to structural, depending on how long they may hold the same value. Structural contextual elements are the most persistent ones, because their values do not change on a regular basis (e.g., the height of a tower). Circumstancial contextual elements are often the most critical, because their values change periodically and these changes interfere with the nominal behavior of the system. Finally, the criticality is a measure of how a contextual element may lead to unintended or unexpected behavior of the system [22].

Following Pinto's guidelines [5], the formalization phase aims at structuring the concepts identified during the conceptualization phase and at organizaing them into a formal or semi-formal model, most of the time using an object-oriented paradigm. The formal representation of our ontology is given in Figure 6.

The proposed ontology can be divided into two parts, represented by two distinct colors on the diagram. Pinto calls these parts *modules*: they are groups of highly connected concepts which convey different kinds of information on their own:

- The *system* module describes the relationships between a system and its activity, as described in the HSI literature [1]. The system is made of structures, upon which are allocated functions. We found in our previous work on context [4] that context is related to a focus, which is given by a structure together with a function. To achieve its function, the structure follows a set of prescribed tasks. However, emergent properties may arise during the realization of those tasks, leading to an actual activity which may differ from what was prescribed by the tasks.

- The *context* module describes the concepts that we elicited in the conceptualization phase. The activities from the system are influenced by the contextual elements. Those belong to one of eight categories, have a certain temporality, and may be more or less relevant and critical to a specific activity. Contextual elements may be also be affected by events. Finally, they are mapped from a domain to a range, with an optional unit.

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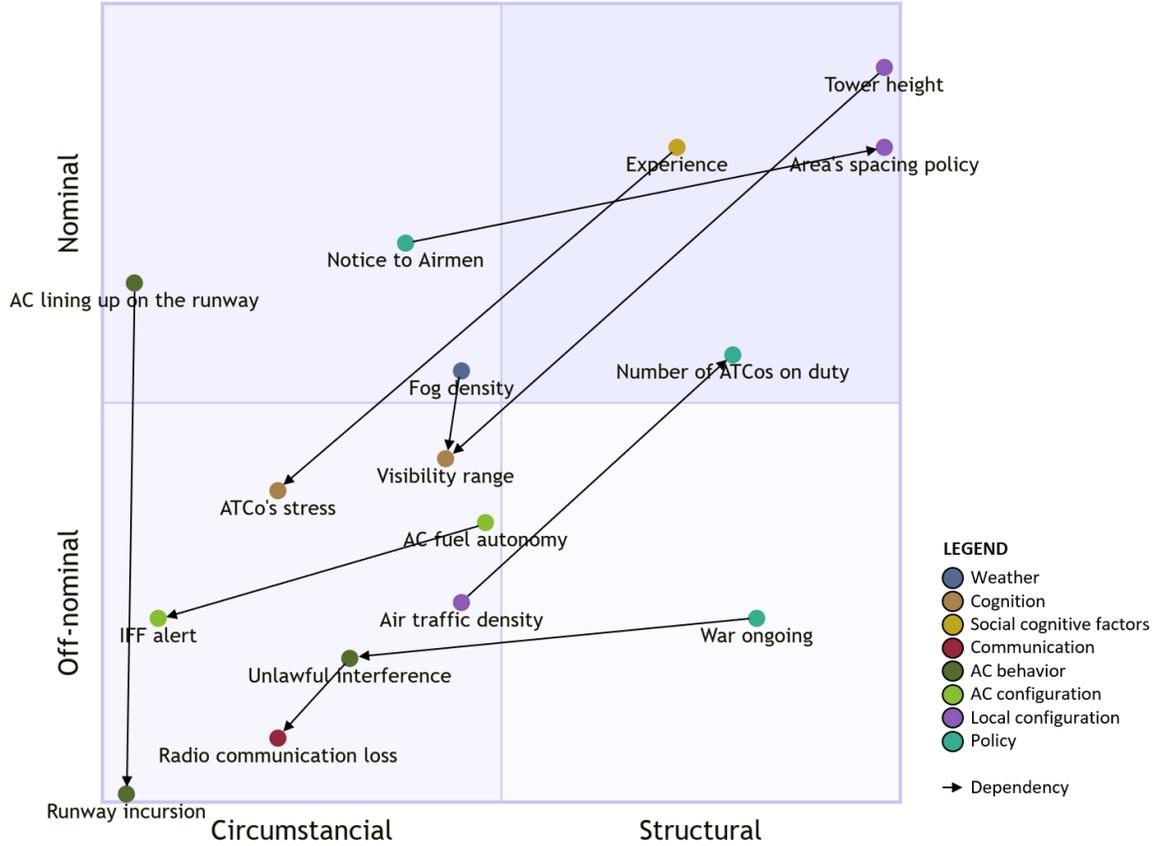
Fig. 5   16 out of 352 contextual elements, classified according to their category, interdependency, temporality and criticality. Only a subset of identified dependencies are shown in the figure.

V. Initial evaluation

The evaluation of an ontology involves three activities according to Pinto [5]: verification, "*which guarantees its correctness according to the accepted understanding about the domain of specialized knowledge sources*", validation, "*which guarantees that it corresponds to what it is supposed to, according to the specifications*", and user assessment. [10] proposes five criteria for verifying an ontology: *consistency*, *completeness*, *conciseness*, *expandability* and *sensitiveness*. [5] emphasizes that some of these criteria are difficult if not impossible to assure, and that evaluation (and by extension, verification) is a long-term process that is performed along the entire ontology lifecycle. [23] adds that ontology building is an iterative process. In this research, we conducted a partial evaluation of the proposed ontology, primarily through *verification* sessions that we describe in this section.

We conducted two-hour verification sessions with each SME that we had interviewed during the conceptualization phase and asked them to assess the validity of our proposed contextual element list and categorization. We first asked them to evaluate the validity and exhaustiveness of each of the eight identified categories of contextual elements. We asked them if they thought some categories were missing and if they found some categories irrelevant. All SMEs conducted this evaluation on all elements.
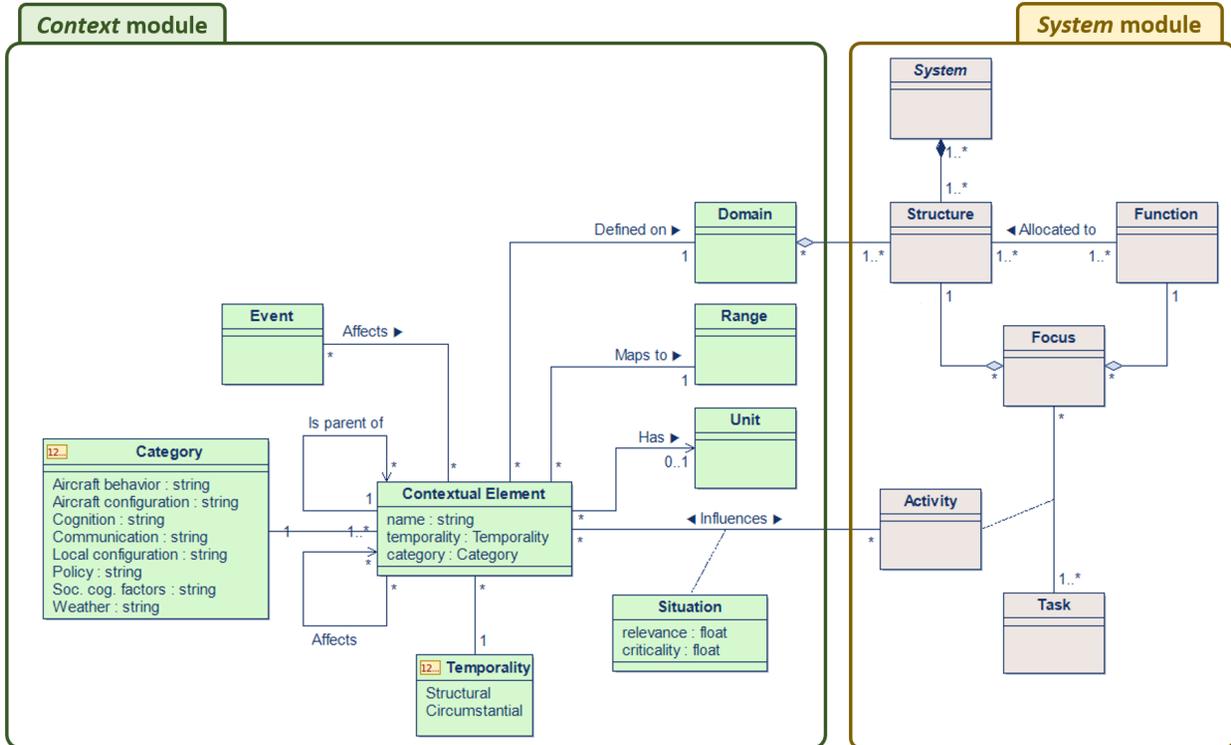
Fig. 6 Our ontology of contextual elements in ATC systems

We then went in more detail into the individual contextual elements and asked them to rate each contextual element according to two fundamental criteria. These criteria were developed based on the six properties of context that we identified in our previous work [4] and that we already discussed in Section II. The two criteria are described below:

- **Criterion 1: How strongly is the contextual element relevant?** When a contextual element has an influence on a task, the outcome of the task may be affected at various levels. We have seen in the previous section that some contextual elements may lead to off-nominal or even emergency situations, while other do not drastically change the behavior of the system. They can also affect nominal operations without turning them into critical situations. Besides, some contextual elements have the property of being "*persistent*", in the sense that they may have an impact on operational scenarios in the long-term. Therefore, we asked SMEs to evaluate this criteria for each contextual element on a 5-point Likert scale, "1" representing "*This contextual element is not relevant*" and "5" representing "*This contextual element is absolutely relevant*".

- **Criterion 2: How often is the contextual element relevant?** Context is *specific* and *curated*, meaning that contextual elements may be relevant (i.e., have an influence) only on a small subset of the tasks carried out by the operators of the system. They can also be relevant to a large number of tasks, but the operators may conduct these tasks only very occasionally. Therefore, we asked SMEs to evaluate this criteria for each contextual element on a 5-point Likert scale, "1" representing "*This contextual element is never relevant*" and "5" representing "*This*

contextual element is always relevant".

The full verification protocol for one session is provided in Table 2.

Table 2   The verification protocol

Question or remark	Expected time
Phase 1: Introduction	
[Presentation of the objectives]	
[Overview of the categories]	5 min
[Description of the evaluation criteria]	
Phase 2: High-level evaluation of categories	
Is there any category missing?	5 min
Would you agree that these categories belong to relevant context?	
Phase 3: High-level scenario elicitation [For each assigned contextual element]	
Criterion 1: How strongly is the contextual element relevant?	
Criterion 2: How often is the contextual element relevant?	90 min
Do you think this contextual element belongs to the appropriate category?	
Phase 4: Additional information [For contextual elements with highest scores]	
Which tasks are affected the most by the contextual element?	20 min
Do you have further remarks about this contextual element?	
Phase 5: Acknowledgements and closure	

Because sessions were limited in time, we asked each SME to evaluate only a subset of the initial list of 341 contextual elements. We partitioned contextual elements between the SMEs according to the following rules:

- Every contextual element must be evaluated by at least one SME;

- Each SME must evaluate some contextual elements from every category;

- All the contextual elements from a given category must be evaluated at least once by the *same* SME, so that the SME can see if contextual elements from this category are missing.

The verification sessions allowed us to identify 11 additional relevant contextual elements (these are the orange lines in the appendix). 23 contextual elements were deemed irrelevant to ATC operations. Participants also suggested to move 24 of the already existing contextual elements to another category. None of them thought that a category was missing, or that one of the eight categories we identified was superfluous. Mergin of synonyms and unit normalization then allowed us to obtain the final list of 334 elements provided in the appendix.

It should also be noted that the three participants reached different levels of agreement on the relevance of the contextual elements depending on the category. Figure 3 gives, for each category, the Krippendorf's Alpha calulated (we used the Alpha calculator and interpretation from Marzi [24]) on scores from Criterion 1 ("*How often is the contextual element relevant?*"). The Krippendorf's Alpha is a real number between -1 and 1 that rates how much participants agree on a classification problem.

We see for example that participants strongly agree on the relevance of contextual elements related to aircraft

Table 3   Krippendorf's Alpha score of Criterion 1 evaluation for each category

Category	Krippendorf's alpha	95% Confidence Interval	Marzi's Interpretation
Aircraft behavior	0.805	[0.343, 0.938]	Strong agreement
Policy	0.668	[-0.092, 1.000]	Moderate agreement
Aircraft configuration	0.656	[0.274, 0.890]	Weak agreement
Cognition	0.510	[-0.208, 0.969]	Weak agreement
Social cognitive factors	0.505	[-0.075, 0.855]	Weak agreement
Communication	0.289	[-0.321, 0.803]	Weak agreement
Weather	0.088	[-0.404, 0.497]	Weak agreement
Local configuration	0.054	[-0.261, 0.308]	Weak agreement

behavior. However, there is no definite agreement on weather- and local configuration-related contextual elements. This does not mean that these categories should be excluded from our ontology. Indeed, as McHugh points out, Krippendorf's Alpha score makes assumptions that may lower the estimate of agreement excessively. Hence, researchers often accept low alpha values in their interrater reliability studies. The weak agreements on some categories may be explained by the high subjectivity of the participants in scoring the relevance of each contextual element due to their individual experiences.

VI. Discussion

As stated in Section III, the purpose of our ontology was to identify the concepts and their relationships that characterize the operational context of complex ATC STSs. Our objective in the long term is to inform SE and HSI processes and system modeling in order to empower designers to create more resilient, efficient and adaptive systems. By modeling context, we can better inform system architecture and behavioral modeling, ensure that pertinent resources are available when needed, and recognize the intricate interplay between a system and its context.

To illustrate the practical utility of the ontology, consider a low-visibility scenario in both conventional tower and remote tower configurations. In a conventional tower, weather-related contextual elements such as fog and weather degradation exhibit high temporality (i.e., rapid evolution) and increasing criticality to common tower controllers' activities (e.g., as fog intensifies). These changes propagate through interdependencies to perception-related elements (e.g., the obstruction of controllers' field of vision) and technical resources such as A-SMGCS Availability and Radar Data Network Availability, which become essential for maintaining situational awareness. The ontology's cause–effect structure captures these cascading relationships, enabling reasoning about emergent workload shifts: as visual cues degrade, cognitive workload and decision-making efficiency elements transition from nominal to critical, prompting task reallocation (e.g., delegating aircraft identification to radar tracking displays rather than relying on direct visual confirmation).

In the remote tower context, the same weather degradation triggers a different propagation of dependencies. Camera

feed quality (Local Configuration) and network availability between Towers (Communication) become primary drivers for situational awareness. Their deterioration may activate fallback policies such as delegating operations to a contingency local tower. By taking into account these interdependencies and temporal dynamics, the ontology encourages proactive resource checks (e.g., verifying sensor redundancy or communication reliability) and structured task redistribution to preserve safety and performance under degraded conditions. Hence, the primary value of the ontology in this example is that it enables reasoning about dynamic context variations and their cascading effects across technical, human and organizational dimensions, in concordance with HSI principles.

However, our methodology exhibits some limitations. Firstly, the exhaustiveness of our sources is constrained, especially during the rating sessions, as we relied on a limited number and variety of SME, whose perspectives may not fully represent the breadth of expertise in the field (e.g., our contextual element list may be enriched by points of view form technicians and instructors, who do not directly participate to the operations). The exhaustiveness of our contextual element list itself is not guaranteed, as our sources may not encompass the full spectrum of relevant factors. This is a crucial point discussed by McCarthy [25], who argues that capturing context is a difficult endeavor, as context has infinite dimensions. The corollary of this is that our list may not fully capture some contextual elements, especially more macro-level and general contextual elements which are difficult to identify due to the specificity of the air traffic control field. This may limit the generalizability of our framework.

The Krippendorf's Alpha scores from Table 3 indicate varying levels of agreement between SME. Some categories, such as Weather and Local Configuration, have low Krippendorf's Alpha scores, suggesting the need for further evaluation to identify where and why SMEs disagree, and to ensure further assess the validity of the categories. The high subjectivity of the Likert scales may also explain the discrepancies between the given scores. Beyond verification, static validation of the ontology diagram against Gomez's criteria (e.g., circularity and redundancy) [10] remains essential to assess its structural integrity. User assessment is a long-term process which will be critical to evaluate the ontology practical utility and alignment with user needs as it will gain more and more maturity. These steps are essential to refine the ontology and enhance its applicability, with implications for system design and modeling discussed subsequently.

VII. Conclusion

This paper addresses the critical challenge of integrating operational context into the design models of complex sociotechnical systems, with a focus on ATC operations. We identified and categorized an initial list of 341 potentially relevant contextual elements, which we subsequently refined through verification sessions with experienced ATC practitioners. These elements, organized into eight categories, offer a representation of the principal factors that influence ATC operations.

The proposed ontology aims at supporting context modeling in operational scenario elicitation in early stages of design. By explicitly modeling contextual elements and their interdependencies, the ontology facilitates the alignment

of prescribed tasks with actual operational activities. Further validation is necessary to explore the relevance of certain categories. This subjectivity highlights the need for tailored contextual models that account for individual and operational variability.

We aim to further develop the ontology and to extend our findings beyond the air traffic control field to other complex sociotechnical systems where context plays a role. The bottom-up approach adopted in this study, starting with a domain-specific ontology, lays the groundwork for potential generalization to broader SE applications. However, limitations remain, including the partial evaluation of the ontology, which focused primarily on verification. Future work should prioritize validation and user assessment to ensure the practical utility and usability of our ontology in real-world design processes. Additionally, formalizing the ontology in a machine-readable format, such as OWL, could enhance its interoperability with existing SE tools and ontologies.

Appendix: The full list of contextual elements

Contextual element Name	Source	Parent	Category	Domain	Range	Unit	Relevance					
							Criterion 1 (Intensity)			Criterion 2 (Frequency)		
							A1	B1	C1	A2	B2	C2
AC behavior			**AC behavior**									
AC acceleration during takeoff run	(Schaik, 2010)	AC acceleration on ground	AC behavior	AC	ℝ	m/s²	1	2	-	1	2	-
AC acceleration in air	(Ellis, 2016)	AC behavior	AC behavior	ACxATCO	ℝ³	m/s²	2	4	-	2	4	-
AC acceleration on ground	Inferred	AC behavior	AC behavior	AC	ℝ	m/s²	1	2	-	1	2	-
AC air collision	SME C, SERA 2024	Collision	AC behavior	ℝ³xACxPHY	Boolean	-	-	-	5	-	-	5
AC climb rate	(Schaik, 2010)	AC acceleration in air	AC behavior	AC	ℝ	m/s²	2	3	-	2	3	-
AC entering the responsibility area of the tower	(Schaik, 2010)	AC behavior	AC behavior	AC, AREA	Boolean	-	5	4	-	2	3	-
AC flare height at landing	(Schaik, 2010)	AC behavior	AC behavior	AC	ℕ	m	1	2	-	1	1	-
AC ground collision	SME C	Collision	AC behavior	ℝ³xACxPHY	Boolean	-	-	-	5	-	-	5
AC lift-off	(Schaik, 2010)	AC behavior	AC behavior	AC	Boolean	-	3	-	-	2	-	-
AC lining up on the runway	(Schaik, 2010)	AC behavior	AC behavior	PILxPHY	Boolean	-	2	-	-	1	-	-
AC slowing down on runway	(Schaik, 2010)	AC acceleration on ground	AC behavior	AC	Boolean	-	1	3	-	1	2	-
AC speed in air	(Ellis, 2016)	AC behavior	AC behavior	ACxATCO	ℝ³	m/s	3	-	-	2	-	-
AC starts to move	(Schaik, 2010)	AC behavior	AC behavior	PIL	Boolean	-	2	-	-	2	-	-
AC starts to turn	(Schaik, 2010)	AC turn-rate	AC behavior	AC	Boolean	-	2	-	-	2	-	-
AC turn-rate	(Schaik, 2010), SME A	AC acceleration on ground	AC behavior	AC	ℕ	°/s	2	3	-	1	2	-
Air Navigation (RNAV) reliance	SERA 2024	AC behavior	AC behavior	AC	Boolean	-	2	-	-	3	-	-
Altimeter Setting Error (ASE)	(Foster, 2020)	Altimeter settings	AC behavior	AC	Boolean	-	4	-	4	3	-	3
Altimeter settings	FAA 7110.65BB	AC behavior	AC behavior	PIL	-	-	5	-	-	4	-	-
Circular manoeuver initiated	SME A	AC behavior	AC behavior	AC	Boolean	-	2	-	2	2	-	3
Collision	SME B	AC behavior	AC behavior	ℝ³xPHYxPHY	Boolean	-	5	-	5	4	-	5
Compliance with orders	SME B, SME C	AC behavior	AC behavior	HUMxATCO	Boolean	-	5	-	-	5	-	-
Conflict	(Josefsson, 2018), SME A	AC behavior	AC behavior	STRxSTR	-	-	4	5	4	4	2	3
Controlled Flight Into Terrain (CFIT)	FAA 7110.65BB	Collision	AC behavior	ACxPHY	Boolean	-	-	-	4	-	-	4
Final approach type	SME B, SME C	AC behavior	AC behavior	PIL	Enum	-	2	-	-	3	-	-
Level bust	(Foster, 2020)	Altimeter Setting Error (ASE)	AC behavior	PIL	Boolean	-	4	-	4	3	-	3
Opposite direction course	FAA 7110.65BB	AC behavior	AC behavior	ACxAC	Boolean	-	5	-	-	3	-	-
Relative visual motion	(Ellis, 2016)	AC behavior	AC behavior	ATCOxACxAC	-	-	4	-	-	2	-	-
Runway excursion	SME C	AC behavior	AC behavior	PHYxPHY	Boolean	-	5	-	5	2	-	5
Runway incursion	SME B, SME C, (Arico, 2019)	AC behavior	AC behavior	PHYxPHY	Boolean	-	5	-	5	2	-	4
Taxiing AC follows designated route	(Schaik, 2010)	Compliance with orders	AC behavior	HUMxATCO	Boolean	-	4	-	4	3	-	2
Touch-and-go operation	FAA 7110.65BB	AC behavior	AC behavior	ACxPHY	Boolean	-	2	-	-	2	-	-
Unauthorized aircraft movement	(Arico, 2019)	Compliance with orders	AC behavior	PIL	Boolean	-	4	-	4	3	-	4
Unlawful interference	SERA 2024	AC behavior	AC behavior	AC	Boolean	-	-	-	3	-	-	3
AC configuration			**AC configuration**									
AC alert	ATC System Documentation	AC configuration	AC configuration	AC	Boolean	-	-	5	5	-	5	5
AC altitude Above Mean Sea Level (AMSL)	ATC System Documentation	AC position	AC configuration	AC	ℕ	m	3	-	4	3	-	3
AC controls availability	ATC System Documentation	AC configuration	AC configuration	AC	Boolean	-	-	5	-	-	5	-
AC fuel autonomy	SME B, SME C	AC mechanical status	AC configuration	AC	ℝ	min	3	-	3	2	-	3
AC height Above Aerodrome Level (AAL)	(Ellis, 2016)	AC position	AC configuration	AC	ℕ	m	3	-	4	3	-	4
AC height Above Ground Level (AGL)	ATC System Documentation	AC position	AC configuration	AC	ℕ	m	3	-	3	3	-	4
AC in patrol	SME A	AC configuration	AC configuration	AC	Boolean	-	2	4	-	2	2	-
AC in the circuit	(Schaik, 2010), SME A	AC position	AC configuration	ACxCIRC	Boolean	-	3	-	3	2	-	2
AC landing lights	(Schaik, 2010)	AC configuration	AC configuration	CENT	-	-	1	2	-	1	2	-
AC mechanical status	(Ellis, 2016)	AC configuration	AC configuration	AC	-	-	3	-	4	4	-	4
AC position	Inferred	AC configuration	AC configuration	AC	-	-	5	5	-	5	5	-
AC position in air	ATC System Documentation, SME A, B, C	AC position	AC configuration	AC	ℝxℕxℕ	(mi, °, m)	3	-	4	5	-	5
AC position on final	(Schaik, 2010)	AC position in air	AC configuration	AC	ℝxℕxℕ	(mi, °, m)	3	-	2	5	-	3
AC position on ground	SME B, C	AC position	AC configuration	AC	ℝ²	m	2	-	2	3	-	2
AC type	(Ellis, 2016), SME C	AC configuration	AC configuration	AC	Enum	-	2	-	-	2	-	-
AC undercarriage state (main gear)	(Ellis, 2016; Schaik, 2010), SME B	AC mechanical status	AC configuration	AC	Enum	-	2	-	-	2	-	-
AC weight category	ATC System Documentation, FAA 7110.65BB	AC mechanical status	AC configuration	PIL	Enum	-	2	-	2	2	-	3
Both engine failure	Verification session A	AC mechanical status	AC configuration	AC	Boolean	-	5	-	-	2	-	-
Engine failure	Verification session A	AC mechanical status	AC configuration	AC	Boolean	-	3	-	4	3	-	4
Engine smoke	(Ellis, 2016)	AC alert	AC configuration	PHY	Boolean	-	3	-	5	3	-	5
Fire alert onboard	SME C	AC alert	AC configuration	AREAxORGA	Boolean	-	5	5	5	3	5	5
Flashing alert	(Foster, 2020)	AC alert	AC configuration	CENT	Boolean	-	-	5	5	-	3	5
Flight phase	(Josefsson, 2018)	AC configuration	AC configuration	AC	-	-	3	-	5	4	-	5
Flight type	SME B, SME C, FAA 7110.65BB, SERA 2024	AC configuration	AC configuration	AC	Enum	-	2	-	-	3	-	-
Gear out beep	SME A	AC alert	AC configuration	ATCOxAC	Boolean	-	-	5	5	-	3	5
IFF alert	ATC System Documentation, SME C	AC alert	AC configuration	ATCOxCENT	Boolean	-	4	-	5	3	-	4
Mission type	SME C	AC configuration	AC configuration	PIL	Enum	-	2	-	-	3	-	-
Number of people onboard	SME C	AC configuration	AC configuration	PIL	ℕ	-	5	-	-	5	-	-
Pilot emergency alert	SME C, (Arico, 2019)	AC alert	AC configuration	PILxCENT	Boolean	-	-	5	5	-	5	5
Presence of AC in distress	SME C, SME A	AC alert	AC configuration	VOL	Boolean	-	-	5	5	-	5	5
Technical failure on AC	SME B	AC mechanical status	AC configuration	PHY	Boolean	-	3	-	-	4	-	-
Type of AC distress	ATC System Documentation, SME C	AC alert	AC configuration	CENT	-	-	-	5	3	-	5	3
Cognition			**Cognition**									
AC in ATCO field of vision	SME B	Perception	Cognition	ACxATCO	Boolean	-	-	5	-	-	5	-
Accuracy of ATCO's short-term predictions	SME A	Cognition	Cognition	ATCO	-	-	-	4	5	-	4	5
Apparent sunshine	SME B	Perception	Cognition	AREA	-	-	-	5	-	-	2	-
ATCO alertness	(Wen-Chin, 2021)	Cognition	Cognition	ATCO	Scale	-	-	5	5	-	5	5
ATCO field of vision obstruction	SME B	Perception	Cognition	ATCO	-	-	-	1	-	-	1	-
ATCO information overload	SME C, (Arico, 2019)	Cognitive workload	Cognition	ATCO	-	-	-	5	-	-	5	-
ATCO personal welfare	SME B, SME C	Cognition	Cognition	ATCO	-	-	-	5	5	-	5	5
ATCO situation awareness	SME C, (Arico, 2019), (Wen-Chin, 2021), SME A	Cognition	Cognition	ATCO	-	-	-	5	5	-	5	5
ATCO's eyes current focus	(Chi, 2023)	Cognition	Cognition	ATCO, PHY	Boolean	-	-	5	5	-	5	2
ATCO's sore eyes	SME B, SME A	ATCO personal welfare	Cognition	ATCO	Boolean	-	-	5	5	-	5	5
ATCO's stress	SME C, (Arico, 2019)	Cognition	Cognition	ATCO	Scale	-	-	5	5	-	5	5
ATCO's understanding of hazard	(Chi, 2023)	Cognition	Cognition	ATCO	-	-	-	5	5	-	5	5
Automation trust	(Arico, 2019), (Chi, 2023)	Cognition	Cognition	PHYxHUM	Scale	-	-	2	3	-	2	3
Binoculars availability	ATC System Documentation, SME B	Perception	Cognition	PHY	Boolean	-	-	-	4	-	-	2
Circadian dysrythmia	(Wen-Chin, 2021), SME A	Fatigue	Cognition	ATCO	Boolean	-	-	5	-	-	5	-
Cognitive workload	SME B, (Foster, 2020), (Arico, 2019), (Chi, 2023), (Wen-Chin, 2021)	Cognition	Cognition	HUM	-	-	-	4	5	-	4	5
Decision-making efficiency	(Arico, 2019)	Cognitive workload	Cognition	HUM	-	-	-	5	-	-	5	-
Direct weather visibility from controller	ATC System Documentation, SME C	Perception	Cognition	ATCO	Boolean	-	-	1	-	-	1	-
Fatigue	(Arico, 2019)	Cognition	Cognition	HUM	Scale	-	-	5	5	-	5	5
Local illumination	SME B	Apparent sunshine	Cognition	VOL	-	-	2	2	-	2	2	-
Loud sound	(Ellis, 2016)	Sound	Cognition	HUM	Boolean	-	2	5	-	2	5	-
Lower body temperature	(Wen-Chin, 2021)	Fatigue	Cognition	PHY	Boolean	-	-	-	-	-	-	-
Monitor availability	ATC System Documentation	Perception	Cognition	PHY	Boolean	-	4	-	4	5	-	4
Napping	(Wen-Chin, 2021)	Fatigue	Cognition	ATCO	Time	min-min	-	4	-	-	4	-
Number of AC under one ATCO's responsibility	SME C, SME A	Cognitive workload	Cognition	ATCO	ℕ	-	-	4	-	-	4	-
Number of night shifts	(Wen-Chin, 2021)	Fatigue	Cognition	ATCO	ℕ*	-	-	1	-	-	1	-
Number on skin of AC	(Schaik, 2010)	Perception	Cognition	PIL	String	-	-	1	-	-	1	-
Paralyzed ATCO	SME C	Cognition	Cognition	ATCO	Boolean	-	-	4	3	-	3	3
Perception	Inferred	Cognition	Cognition		-	-	-	5	5	-	5	5
Pilot's intention	SME A	Cognition	Cognition	AC	Enum	-	-	4	2	-	4	2
Presence of smoke from tires when touching down	(Schaik, 2010), (Ellis, 2016)	Perception	Cognition	PHY	Boolean	-	-	3	-	-	3	-
Prioritisation of a task	(Foster, 2020)	Decision-making efficiency	Cognition	ATCO	Boolean	-	-	5	-	-	5	-
Quality of received information	(Arico, 2019)	Perception	Cognition	ATCO	Scale	-	-	5	-	-	5	-
Reaction time	(Arico, 2019)	Cognition	Cognition	HUM	ℕ*	ms	-	5	-	-	5	-
Runway Visual Range	ATC System Documentation, (Schaik, 2010), FAA 7110.65BB	Perception	Cognition	CENT	ℕ*	m	3	-	5	2	-	5
Sleeping time	(Wen-Chin, 2021)	Fatigue	Cognition	ATCO	-	-	-	5	-	-	5	-
Sound	SME B, SME A	Perception	Cognition	VOL	-	-	-	5	-	-	5	-
Sound of takeoff power	(Ellis, 2016)	Sound	Cognition	ATCO	Boolean	-	1	3	-	1	2	-
Subjective sleepiness	(Wen-Chin, 2021)	Fatigue	Cognition	ATCO	Scale	-	-	5	-	-	5	-

Name	Source	Attribute	Category	Actor	Type	Unit						
Sudden change in workload	SME A	Cognition	Cognition	ATCO	Boolean	-	-	-	5	-	-	5
Task complexity	(Arico, 2019), (Wen-Chin, 2021)	Cognition	Cognition	COG	-	-	-	5	-	-	5	-
Vehicle horn sound	SME, SME A	Sound	Cognition	ATCO	Boolean	-	-	-	1	-	-	1
Visibility range	(Schaik, 2010), (Arico, 2019), SERA 2024	Perception	Cognition	ATCO	N°	m	3	5	-	2	5	-
Visualization station availability	ATC System Documentation	Perception	Cognition	PHY	Boolean	-	-	-	4	-	-	3
Communication			**Communication**									
ATCO's current radio frequency	SME A	Communication	Communication	ATCO	N²	Hz	5	5	-	5	5	-
Communication system maintenance	Verification session C	Communication	Communication	PHY	-	-	-	-	4	-	-	5
Coordination with meteorological services	SERA 2024	Communication	Communication	CENT	-	-	5	5	-	3	5	-
Departure clearance transmitted	SME B	Communication	Communication	PILxATCO	Boolean	-	4	2	-	2	2	-
Electronic Stripping System availability	ATC System Documentation, SME A	Communication	Communication	PHY	Boolean	-	-	-	4	-	-	5
Flight Message Transfer availability	SME B	Communication	Communication	CENT	Boolean	-	4	-	3	3	-	3
Incoming transfer acknowledged by receiver	SME B	Instruction acknowledgement received	Communication	ATCOxATCO	Boolean	-	-	4	4	-	3	2
Information transmitted to wrong receiver	SME B	Communication	Communication	ATCO	Boolean	-	5	5	-	4	4	-
Instruction acknowledgement received	(Foster, 2020)	Communication	Communication	ATCOxPIL	Boolean	-	5	5	-	5	5	-
Intercom availability	ATC System Documentation	Communication	Communication	PHY	Boolean	-	3	3	3	5	4	4
Lack of strict adherence to ICAO phraseology	(Foster, 2020)	Phraseology inconsistency	Communication	ATCO	Scale	-	-	5	2	-	5	5
Latest instruction received	(Foster, 2020)	Communication	Communication	PIL	String	-	5	5	-	5	5	-
Misunderstanding due to foreign languages	SME A	Communication	Communication	HUMxHUM	Boolean	-	5	5	-	4	5	-
Network availability between towers	Verification session A	Communication	Communication	CENT	Boolean	-	2	-	-	2	-	-
Phone availability	ATC System Documentation	Communication	Communication	PHY	Boolean	-	3	4	4	5	4	4
Phraseology inconsistency	(Foster, 2020)	Communication	Communication	ATCO	Boolean	-	-	5	1	-	5	1
Pilot asking for taxi / departure	(Ellis, 2016)	Communication	Communication	PILxCENT	Boolean	-	-	3	3	-	2	2
Pilot Report (PIREP) content	FAA 7110.65BB	Communication	Communication	PILxCENT	-	-	-	5	2	-	5	2
Quality of ATCO coordination & cooperation	FAA 7110.65BB	Communication	Communication	CENT	-	-	-	5	3	-	5	2
Radar data network availability	ATC System Documentation	Communication	Communication	CENT	Boolean	-	-	-	4	-	-	3
Radio availability	SME C, SERA 2024	Communication	Communication	PHY	Boolean	-	5	-	5	5	-	5
Radio communication loss	Verification session C	Communication	Communication	PHY	Boolean	-	-	-	5	-	-	3
Radio communication loss during a transfer	Verification session C	Communication	Communication	PHY	Boolean	-	-	-	5	-	-	2
Radio frequency bottleneck	SME A	Communication	Communication	COG	Scale	-	3	-	3	2	-	3
Track exchange network availability	Verification session A	Communication	Communication	CENT	Boolean	-	2	-	-	2	-	-
Transmission overlap	(Foster, 2020)	Communication	Communication	HUMxHUM	Boolean	-	-	4	4	-	3	3
Transponder availability	SERA 2024	Communication	Communication	AC	Boolean	-	-	-	4	-	-	5
VHF radio facilities availability	ATC System Documentation	Communication	Communication	PHY	Boolean	-	-	-	5	-	-	5
Local configuration			**Local configuration**									
AC horizontal separation	SME C, (Foster, 2020)	AC separation	Local configuration	ACxAC	N	m	5	1	-	5	1	-
AC separation	SME B	Air traffic density	Local configuration	ACxAC	N	m	5	1	-	5	1	-
AC vertical separation	SME C, (Foster, 2020)	AC separation	Local configuration	ACxAC	N	m	5	1	-	5	1	-
Air state color	SME A, SME C	Local configuration	Local configuration	PHY	Enum	-	3	3	-	4	3	-
Air traffic density	ATC System Documentation, (Arico, 2019), FAA 7110.65BB, (Josefsson, 2018)	Local configuration	Local configuration	VOL	-	-	4	5	-	3	5	-
Airspace classification	FAA 7110.65BB, SERA 2024	Local configuration	Local configuration	ACxAC	Enum	-	5	5	-	5	5	-
Animal on manoeuvring area or vicinity	(Schaik, 2010), SME C	Presence of obstacles on ground	Local configuration	AREA	Boolean	-	-	5	-	-	-	4
Area Border Crossing Alert (ABCA)	ATC System Documentation	Local configuration	Local configuration	AREA	Boolean	-	4	5	2	3	2	2
A-SMGCS (Ground surveillance) availability	ATC System Documentation	Local configuration	Local configuration	PHY	Boolean	-	-	2	-	-	-	4
ATIS validity	ATC System Documentation	Local configuration	Local configuration	CENT	Boolean	-	5	1	-	2	1	-
Bird air activity	ATC System Documentation, (Ellis, 2016), SME B	Presence of obstacles	Local configuration	VOL	-	-	-	-	4	-	-	4
Chaff presence	FAA 7110.65BB	Radar clutter	Local configuration	VOL	Boolean	-	-	5	3	-	4	2
Emergency instruction up-to-date	SME A	Local configuration	Local configuration	CENT	Boolean	-	4	-	5	-	-	4
Fire brigade response time	SME C	Local configuration	Local configuration	ORGA	N°	min	-	1	5	-	1	2
Flight plan status	SME C, FAA 7110.65BB	Local configuration	Local configuration	AC	Boolean	-	-	1	2	-	1	2
Flock of small birds on manoeuvring area or vicinity	(Ellis, 2010; Schaik, 2010), SME C	Bird air activity	Local configuration	VOL	Boolean	-	5	5	4	2	3	4
Foreign objects on the runway	(Schaik, 2010)	Presence of obstacles on runway	Local configuration	PHY	Boolean	-	-	4	-	-	-	4
Ground traffic density	ATC System Documentation, SME C	Air traffic density	Local configuration	AREA	Enum	-	4	5	-	2	2	-
Hardware capabilities	Inferred	Local configuration	Local configuration	PHY	-	-	-	3	3	-	3	5
ILS availability	SME B	Local configuration	Local configuration	PHY	Boolean	-	3	3	3	2	2	2
Intersecting runways	FAA 7110.65BB	Local configuration	Local configuration	PHYxPHY	Boolean	-	5	1	-	3	1	-
Large-size bird on manoeuvring area or vicinity	(Schaik, 2010), Interview C	Bird air activity	Local configuration	AREA	Boolean	-	-	5	4	-	3	4
Light beacon configuration	SME B, SERA 2024	Terrain specificity	Local configuration	AREA	-	-	-	1	2	-	1	2
Light beacon intensity	SME B	Light beacon configuration	Local configuration	AREA	Scale	-	5	-	2	2	-	-
Navigation aid configuration	SERA 2024	Local configuration	Local configuration	AREA	-	-	-	1	4	-	1	4
Network quality	ATC System Documentation	Hardware capabilities	Local configuration	PHY	Scale	-	-	4	3	-	4	3
Night or day	Verification session A	Local configuration	Local configuration	CENT	Enum	-	2	-	-	3	-	-
Non-stationary obstacles on the manoeuvring area	Inferred	Presence of obstacles on ground	Local configuration	AREA	Boolean	-	-	-	4	-	-	4
Number of AC in distress	SME C, SME B	Local configuration	Local configuration	AREA	N	-	4	-	4	3	-	4
Number of AC movements per day	SME B	Air traffic density	Local configuration	CENT	N	-	4	5	-	3	5	-
Number of AC under local control's responsibility	SME B, SME A	Local configuration	Local configuration	CENT	N	-	4	5	-	5	5	-
Number of current go-arounds	(Schaik, 2010), (Foster, 2020), (Arico, 2019), (Josefsson, 2018)	Air traffic density	Local configuration	CENT	N	-	-	1	3	-	1	3
Number of current missed-approaches	(Schaik, 2010)	Local configuration	Local configuration	CENT	N	-	4	4	-	1	4	-
Number of runways	SERA 2024, SME A	Local configuration	Local configuration	CENT	N°	-	2	4	-	2	4	-
Nursing capabilities	SME C	Local configuration	Local configuration	CENT	-	-	-	2	1	-	2	1
Power outage	SME C	Local configuration	Local configuration	PHY	Boolean	-	4	5	5	5	5	5
Precision Approach Radar (PAR) availability	ATC System Documentation	Radar availability	Local configuration	PHY	Boolean	-	-	-	3	-	-	2
Precision Approach Radar (PAR) range	ATC System Documentation	Hardware capabilities	Local configuration	PHY	$\mathbb{R}^+$	m	-	1	3	-	1	3
Prescribed transition altitude	(Foster, 2020)	Local configuration	Local configuration	AREA	N	m	-	2	1	-	2	1
Presence of obstacles	Inferred	Local configuration	Local configuration	VOL	Boolean	-	5	-	4	3	-	2
Presence of obstacles on airspace	Inferred	Presence of obstacles	Local configuration	VOL	Boolean	-	-	-	4	-	-	4
Presence of obstacles on ground	Inferred	Presence of obstacles	Local configuration	AREA	Boolean	-	-	-	4	-	-	4
Presence of obstacles on runway	ATC System Documentation, SME B, SME C	Presence of obstacles on ground	Local configuration	PHY	Boolean	-	-	-	4	-	-	4
Primary Surveillance Radar (PSR) availability	ATC System Documentation	Radar availability	Local configuration	PHY	Boolean	-	-	-	4	-	-	3
Primary Surveillance Radar accuracy	ATC System Documentation	Hardware capabilities	Local configuration	PHY	N°	%	3	5	-	3	5	-
QFU (i.e. magnitude orientation of active runway)	ATC System Documentation	Hardware capabilities	Local configuration	PHY	N°	°	1	1	-	5	1	-
Radar availability	SME B	Local configuration	Local configuration	PHY	Boolean	-	4	4	3	4	3	4
Radar clutter	ATC System Documentation	Hardware capabilities	Local configuration	RADAR	-	-	3	3	-	2	3	-
Radio channel congestion	SME C, (Foster, 2020)	Hardware capabilities	Local configuration	COG	Scale	-	3	5	-	2	5	-
Radio channel congestion when few available	Verification session B	Hardware capabilities	Local configuration	COG	Scale	-	4	-	-	3	-	-
Radio emergency facilities	SME C	Hardware capabilities	Local configuration	AREA	-	-	-	2	4	-	1	4
Radio navigation equipment accuracy	SME B	Hardware capabilities	Local configuration	PHY	N°	%	1	3	-	1	3	-
Radio navigation equipment layout	SME B	Local configuration	Local configuration	CENT	-	-	-	1	3	-	1	3
Radio redundancy	SME C	Hardware capabilities	Local configuration	PHY	N	-	2	5	-	5	5	-
Radio sound quality	SME C	Hardware capabilities	Local configuration	PHY	Scale	-	4	4	-	4	4	-
Runway barrier status	SME C	Local configuration	Local configuration	PHY	Enum	-	3	3	-	2	2	-
Runway occupation	ATC System Documentation	Runway status	Local configuration	PHY	Boolean	-	5	3	4	4	3	2
Runway separation	ATC System Documentation	Local configuration	Local configuration	PHYxPHY	N	m	2	4	-	2	4	-
Runway status	ATC System Documentation, SME C	Local configuration	Local configuration	PHY	Enum	-	-	3	3	-	3	4
Runway status of adjacent airfields	ATC System Documentation, SME B	Runway status	Local configuration	CENTxPHY	Enum	-	-	2	3	-	2	4
Safety net alert	(Foster, 2020)	Local configuration	Local configuration	AREA	Enum	-	-	5	3	-	5	3
Secondary Surveillance Radar (SSR) availability	ATC System Documentation	Radar availability	Local configuration	PHY	Boolean	-	-	-	4	-	-	3
Security capabilities	SME C	Local configuration	Local configuration	CENT	-	-	-	3	3	-	3	3
Software capabilities	Inferred	Local configuration	Local configuration	PHY	-	-	-	1	3	-	1	3
Special Activity Airspace (SAA)	FAA 7110.65BB	Local configuration	Local configuration	VOL	Enum	-	-	2	3	-	2	3
Special weather information	FAA 7110.65BB	Local configuration	Local configuration	CENT	Boolean	-	-	5	3	-	5	3
Stationary obstacles on the manoeuvring area	(Schaik, 2010)	Presence of obstacles on ground	Local configuration	AREA	Boolean	-	-	-	4	-	-	4
Surface Movement Radar (SMR) availability	ATC System Documentation	Radar availability	Local configuration	PHY	Boolean	-	-	-	3	-	-	2
Surveillance threat alert	SME C	Local configuration	Local configuration	AREA	Boolean	-	-	5	-	5	-	3
Synthesis Center availability	ATC System Documentation	Local configuration	Local configuration	PHY	Boolean	-	-	-	3	-	-	3
TACtical Air Navigation (TACAN) availability	SME B	Local configuration	Local configuration	PHY	Boolean	-	-	-	5	-	-	4
Tactical Data Link (TDL) support	(Foster, 2020), SERA 2024	Hardware capabilities	Local configuration	PHY	Boolean	-	1	4	-	1	5	-
Tactical Data Link in abroad operations	Verification session C	Tactical Data Link (TDL) support	Local configuration	PHY	Boolean	-	-	4	-	-	4	-
Taxiway availability	ATC System Documentation	Local configuration	Local configuration	PHY	Boolean	-	-	-	5	-	-	5
Taxiway obstruction	SME B, SME A	Presence of obstacles on ground	Local configuration	PHY	Boolean	-	3	-	5	2	-	3
Terminal Manoeuvring Area (TMA) congestion	(Foster, 2020)	Air traffic density	Local configuration	VOL	-	-	-	4	4	-	4	4
Terrain Awareness and Warning Systems availability	FAA 7110.65BB	Local configuration	Local configuration	AC	Boolean	-	-	-	5	-	-	5
Terrain relief	ATC System Documentation	Terrain specificity	Local configuration	AREA	-	-	1	3	-	1	3	-
Terrain specificity	Inferred	Local configuration	Local configuration	PHY	-	-	-	5	4	-	5	4
Tower cabin availability	ATC System Documentation	Local configuration	Local configuration	PHY	Boolean	-	-	-	4	-	-	5
Tower height	ATC System Documentation	Local configuration	Local configuration	PHY	N°	m	-	4	1	-	2	1
Traffic alert and Collision Avoidance System (TCAS)	(Foster, 2020)	Local configuration	Local configuration	PIL	Enum	-	4	5	4	2	5	3
Vehicle on runway	SME C	Vehicle on the manoeuvring area	Local configuration	PHYxPHY	Boolean	-	-	-	5	-	-	4
Vehicle on the manoeuvring area	(Schaik, 2010)	Non-stationary obstacles on the manoeuvring area	Local configuration	AREAxPHY	Boolean	-	5	-	4	3	-	3
VHF Omnidirectional Range (VOR) availability	SME B	Local configuration	Local configuration	PHY	Boolean	-	-	-	2	-	-	4
VIP presence	SME C	Local configuration	Local configuration	AREA	Boolean	-	-	4	4	-	4	4
Water, snow or slush on runway	(Schaik, 2010)	Stationary obstacles on the manoeuvring area	Local configuration	PHY	Boolean	-	-	-	4	-	-	4
Policy			**Policy**									
Airline-specific procedures	(Foster, 2020)	Policy	Policy	CENT	-	-	-	-	4	-	-	5
Ambient recording policy	SME B	Policy	Policy	CENT	-	-	-	-	4	-	-	3
Area traversal request from civilian authorities	SME C	Policy	Policy	CIV-ORGA, MIL-ORGA	Boolean	-	-	-	2	-	-	4
Area's spacing policy	SME B, FAA 7110.65BB, SME A	Policy	Policy	VOL	-	-	-	-	4	-	-	5
ATC clearance priorities	SERA 2024	Policy	Policy	CENT	List	-	-	-	4	-	-	5
Civilian or military control center	SME B	Policy	Policy	CENT	Enum	-	-	-	4	-	-	3
Conflicting regulation	(Foster, 2020)	Policy	Policy	CENT	Boolean	-	-	-	4	-	-	3
Local control tolerance to tourism ACs	SME B	Policy	Policy	CENT	Scale	-	-	-	4	-	-	4
Military-civilian integration	SME B	Policy	Policy	CENT	Boolean	-	-	3	5	-	3	5
Notice to Airmen (NOTAM)	ATC System Documentation	Policy	Policy	CENT	Boolean	-	-	4	4	-	4	4
Number of local ATCOs on duty	SME B	Policy	Policy	CENT	N°	-	-	5	5	-	5	5
Proportion of commercial flights	(Foster, 2020), SME B	Civilian or military control center	Policy	CENT	N°	%	-	2	2	-	2	2
Proportion of military flights	(Foster, 2020)	Civilian or military control center	Policy	CENT	N°	%	-	2	2	-	2	2
Proportion of private or domestic flights	SME B, (Foster, 2020)	Civil control tolerance to tourism ACs	Policy	CENT	N°	%	-	2	2	-	2	2
Proportion of training flights	SME B	Policy	Policy	CENT	N°	%	-	4	2	-	2	2
Remote control of multiple airports	(Arico, 2019), (Josefsson, 2018)	Policy	Policy	CENT	Boolean	-	-	4	4	-	5	5
Safety policy	(Wen-Chin, 2021), SERA 2024	Policy	Policy	CENT	-	-	-	3	-	4	5	-
Search & Rescue (S&R) policy	SME C	Policy	Policy	CENT	-	-	-	3	-	3	5	-
Temporary airspace restriction	SERA 2024	Policy	Policy	VOL	Boolean	-	-	4	-	5	3	-
Temporary Operating Instruction (TOI)	(Foster, 2020)	Policy	Policy	CENT	Boolean	-	-	5	-	5	4	-
Unmanned Aircraft System (UAS) policy	FAA 7110.65BB, SERA 2024	Policy	Policy	AREA	-	-	4	-	3	4	-	3

Parameter	Source	Category	Sub-category	Entity	Type	Unit						
Wake turbulence separation minima	FAA 7110.65BB	Policy	Policy	ACxAC	ℕ*	m	-	-	2	-	-	2
War ongoing	SME B, SME A	Policy	Policy	CENT	Boolean	-	-	-	4	-	-	5
Social cognitive factors		**Social cognitive factors**										
ATCO acquaintance with airfield	SME C	Experience	Social cognitive factors	ATCO	-	-	2	4	-	2	4	-
ATCO administrative responsibilities	SME A, SME B	Human resource management	Social cognitive factors	ATCO	-	-	2	-	3	4	-	2
ATCO judgement	(Foster, 2020)	Experience	Social cognitive factors	ATCO	-	-	5	-	-	5	-	-
ATCO license	SME C, SME A	Experience	Social cognitive factors	ATCOxCENT	Boolean	-	5	-	-	5	-	-
ATCO multitasking abilities	SME C, SME A	Social cognitive factors	Social cognitive factors	ATCO	-	-	5	5	-	5	4	-
ATCO nationality	(Foster, 2020)	Social concerns	Social cognitive factors	ATCO	Enum	-	3	3	-	4	3	-
ATCO qualifications	SME B	Experience	Social cognitive factors	ATCO	Array	-	5	5	-	3	4	-
ATCO training needs	ATC System Documentation	Experience	Social cognitive factors	ATCO	-	-	2	3	-	3	4	-
ATCO training time	SME C	Experience	Social cognitive factors	ATCO	ℕ*	min	1	4	-	1	5	-
ATCO wage	SME C, SNCTA	Social concerns	Social cognitive factors	ATCO	ℝ*	currency	1	2	-	1	2	-
ATCO weekly hours	SME C	Worker's schedule	Social cognitive factors	ATCO	ℕ*	min	3	4	-	5	5	-
ATCO years of practice	SME A, SME B, SME C	Experience	Social cognitive factors	ATCO	ℕ*	yr	5	5	-	5	4	-
ATCO's pressure	(Foster, 2020)	Worker's schedule	Social cognitive factors	ATCO	Scale	-	3	5	-	5	4	-
Attractiveness of the ATCO profession	SME B	Social concerns	Social cognitive factors	CENT	-	-	3	1	-	2	1	-
Callsign confusion	(Josefsson, 2018)	Social cognitive factors	Social cognitive factors	ACxACxATCO	Boolean	-	-	-	4	-	-	2
Corporate culture	ATC System Documentation, SME B	Social concerns	Social cognitive factors	CENT	-	-	2	3	-	5	3	-
Crew skills	ATC System Documentation	Experience	Social cognitive factors	CENT	-	-	5	-	-	5	-	-
Cultural barriers	(Foster, 2020)	Social concerns	Social cognitive factors	ATCO	-	-	3	5	-	4	5	-
Experience	SME A, SME B, SME C	Social cognitive factors	Social cognitive factors	HUM	-	-	5	-	-	4	-	-
Extended shifts	(Arico, 2019)	Worker's schedule	Social cognitive factors	CENT	Boolean	-	3	4	-	2	4	-
Frequency of personnel rotation	SME B	Worker's schedule	Social cognitive factors	CENT	ℕ	#/day	3	-	-	5	-	-
Human resource management	Inferred	Social cognitive factors	Social cognitive factors	CENT	-	-	3	-	4	4	-	4
Interface ergonomics	(Arico, 2019)	Social cognitive factors	Social cognitive factors	PHY	-	-	3	-	-	5	-	-
Language proficiency	(Foster, 2020), SERA 2024	Cultural barriers	Social cognitive factors	ATCO	Boolean	-	5	-	-	5	-	-
Leader acquaintance with team members	SME B	Experience	Social cognitive factors	ATCOxORGA	-	-	2	-	-	5	-	-
Local language	SERA 2024	Cultural barriers	Social cognitive factors	CENT	Enum	-	5	-	5	5	-	5
Need for verification of printed information	(Arico, 2019)	Social cognitive factors	Social cognitive factors	COGxATCO	Boolean	-	1	-	2	1	-	3
Night operations permitted	SERA 2024	Worker's schedule	Social cognitive factors	CENT	Boolean	-	2	-	2	3	-	2
Personnel profile	SME B	Human resource management	Social cognitive factors	CENT	-	-	2	-	-	3	-	-
Pilot's acquaintance with local center	SME A	Experience	Social cognitive factors	HUM	Scale	-	2	-	-	2	-	-
Professionalism	(Foster, 2020)	Social cognitive factors	Social cognitive factors	HUM	-	-	3	-	-	5	-	-
Reliance on informal procedures	(Foster, 2020)	Experience	Social cognitive factors	ATCO	Boolean	-	3	-	-	5	-	-
Role assignement	SME A	Human resource management	Social cognitive factors	CENT	-	-	3	-	-	5	-	-
Social concerns	Inferred	Social cognitive factors	Social cognitive factors		-	-	3	-	-	2	-	-
Team leader management style	SME B	Human resource management	Social cognitive factors	ATCO	-	-	2	-	-	2	-	-
Time on duty	(Wen-Chin, 2021)	Worker's schedule	Social cognitive factors	ATCO	Time	min	3	-	-	5	-	-
Timing of sleep prior to duty	(Wen-Chin, 2021)	Worker's schedule	Social cognitive factors	ATCO	Time	min	2	-	-	2	-	-
Worker's last break	SME C, SME A	Worker's uninterrupted work time	Social cognitive factors	HUM	Time	min	3	-	-	2	-	-
Worker's schedule	SME B	Human resource management	Social cognitive factors	ATCO	-	-	3	-	-	3	-	-
Worker's uninterrupted work time	SME B, SME C	Worker's schedule	Social cognitive factors	HUM	ℕ	min	3	-	-	2	-	-
Weather		**Weather**										
Air temperature	ATC System Documentation	Weather	Weather	VOL	ℝ	°C	2	1	-	2	1	-
Cloud ceiling altitude	SME B, SERA 2024	Cloud conditions	Weather	AREA	ℕ*	m	3	-	-	3	-	-
Cloud conditions	(Schaik, 2010), ATC System Documentation, SME B, SME C	Weather	Weather	VOL	-	-	4	5	-	2	5	-
Cloud coverage	(Schaik, 2010)	Cloud conditions	Weather	AREA, ℕ*	Enum	-	3	-	-	3	-	-
Cloud type	ATC System Documentation	Cloud conditions	Weather	AREA, ℕ*	Enum	-	4	-	-	3	-	-
Coefficient of haze (CoH)	ATC System Documentation	Weather	Weather	VOL	ℝ*	-	3	5	-	4	5	-
Crosswind intensity	SME C	Wind	Weather	VOL	Scale	-	5	-	3	5	-	5
Dew point temperature	ATC System Documentation	Weather	Weather	VOL	ℝ	°C	2	2	-	2	1	-
Fog	SME C, FAA 7110.65BB, SERA 2024	Weather	Weather	VOL	-	-	4	5	-	3	5	-
Fog density	ATC System Documentation, SME B	Fog	Weather	VOL	ℝ*	g/m³	4	-	-	3	-	-
Freezing level	ATC System Documentation	Weather	Weather	AREA	ℕ	m	3	5	-	2	3	-
Frost	SME B, SME C	Weather	Weather	AREA	-	-	2	5	-	2	3	-
Ground fog	FAA 7110.65BB	Fog	Weather	VOL	ℝ*	g/m³	3	-	-	4	-	-
Gusts of wind	ATC System Documentation, SME A	Wind	Weather	VOL	Boolean	-	3	3	4	5	-	5
Hail	SME C	Weather	Weather	VOL	-	-	3	3	-	2	2	-
Hazardous inflight weather advisory	FAA 7110.65BB	Weather	Weather	ATCO	Boolean	-	5	5	-	3	5	-
Headwind strength	(Foster, 2020)	Wind	Weather	VOL	Scale	-	4	-	5	5	-	4
Icing	Verification session A	Weather	Weather	AREA	-	-	2	-	-	2	-	-
Layout of enlightened areas among clouds	SME B	Cloud conditions	Weather	VOL	-	-	4	-	-	2	-	-
Microbursts	FAA 7110.65BB	Gusts of wind	Weather	VOL	Boolean	-	3	-	-	3	-	-
Precipitation type	(Schaik, 2010)	Rain	Weather	AREA	Enum	-	2	-	-	2	-	-
QFE (i.e. atmospheric pressure at ground)	ATC System Documentation	Weather	Weather	AREA	ℕ*	hPa	4	1	1	5	1	5
QNH (i.e. atmospheric pressure at sea level)	ATC System Documentation, (Foster, 2020)	Weather	Weather	AREA	ℕ*	hPa	5	1	1	5	1	5
Rain	ATC System Documentation, SME B, SME C	Weather	Weather	AREA	-	-	3	3	-	2	2	-
Rain intensity	SME B, SME C	Rain	Weather	AREA	Scale	-	3	-	-	3	-	-
Rain type	SME C	Rain	Weather	AREA	Enum	-	2	-	-	2	-	-
Snow	SME C	Weather	Weather	AREA	-	-	5	5	3	4	5	5
Storm conditions	(Foster, 2020)	Weather	Weather	VOL	-	-	5	5	-	3	5	-
Thunder	SME B, SME C, SME A	Weather	Weather	VOL	-	-	4	-	-	3	-	-
Thunderstorm	FAA 7110.65BB	Thunder	Weather	VOL	Boolean	-	4	-	3	3	-	5
Turbulence	FAA 7110.65BB	Wind	Weather	VOL	Boolean	-	4	-	3	3	-	5
Unexpected thunders	SME B	Thunder	Weather	VOL	Boolean	-	4	-	3	4	-	5
Volcanic ash	FAA 7110.65BB, SERA 2024	Weather	Weather	VOL	Boolean	-	5	-	3	2	-	5
Weather degradation	SME B, SME C, SERA 2024	Weather	Weather	VOL	-	-	3	-	-	2	-	-
Weather situation in other areas	SME A	Weather	Weather	AREA	-	-	2	-	-	2	-	-
Wind	Inferred	Weather	Weather	VOL	-	-	5	-	5	5	-	5
Wind direction	ATC System Documentation, FAA 7110.65BB, FAA 7110.65BB	Wind	Weather	VOL	ℕ*	deg	5	-	3	5	-	5
Wind speed	ATC System Documentation, FAA 7110.65BB	Wind	Weather	VOL	ℕ*	m/s	5	-	3	5	-	5
Windshear	FAA 7110.65BB	Wind	Weather	VOL	Boolean	-	5	-	2	4	-	5

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