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INFORMATION PAPER

WP No: 105
IFATCA'24

Report of the Joint Cognitive Human Machine System Group (JCHMS)

Presented by
JCHMS

SUMMARY

The future influence of new technologies such as Machine Learning and Artificial Intelligence will pose new challenges to the working environment in Air Traffic Control.

Under the umbrella of IFATCA, a group of motivated people has started to discuss and do research on these challenges. This group has produced several conferences papers and has finalised a draft guidance material. The aim being that this guidance material will serve the Federation in the future to assist in educating its membership and contribute to the regulation, certification, and ongoing research initiatives. This paper should be a major contribution to the discussion on the future of technology.

1. Introduction

1.1. A group of dedicated professionals has started to tackle this important subject since over a year.

1.2. Composed of Ms Nora Berzina (MUAC ATCO, EGATS), Dr. Anthony Smoker (EASA representative IFATCA, GATCO UK), Dr. Stathis Malakis (SESAR representative ATCO, Greece), Mr. Andrea Poti (EASA representative IFATCA, Italy), Mr. Tom Laursen (former EVP Europe, Denmark), have meet 36 times and were joined by Dr. Marcello Scala (Italy) and Sergio Velotto (Italy) at the later stage of the work. Mr. Marc Baumgartner (SESAR/EASA Coordinator, Switzerland) has acted as coordinator of the group. Dr. Marcello Scala is resigned from the group.

1.3. Working paper 165 for Jamaica Conference 23 informed Directors that guidance material will be created. Andrea Poti member of the group presented the paper.

1.4. The guidance material V6 is attached to the IP

1.5. Further scientific publications are currently being prepared.

1.6. The V6 of the paper will be discussed at the 4th Digitalisation Conference, taking place on the 22.3.2024 in Geneva.

2. Discussion

2.1. The JCHMS has met over 36 times since its inception. The aim being that we produce guidance material for IFATCA and the Member Associations with the aim to educate, inform and debate on the future of our profession with the advent of new technology.

2.2. On the 22nd of March the 4th Digitalisation Conference will take place in Geneva with the objective to debate the Guidance Material proposed. An update from this event will be provided to conference.

2.3. With the advent of new technology in particular Artificial Intelligence and Machine Learning Air Traffic Management and in particular Air traffic control work might fundamentally change. IFATCA as the global technical and professional voice of Air Traffic Controllers needs to be able to influence the current Research and Innovation work in this domain with professional inputs.

2.4. The guidance material will provide such information for the member associations, the regulators, and the Air Navigation Service providers across the globe.

3. Conclusion

3.1. Attached to this paper is the version 6 of the Guidance Material. Directors are invited to comment on the paper.

3.2. Further work will take place in form of research publication, Educational sessions for member associations and exchange with regulators and ANSP.

Attachment

Guidance Material for the design and use of Joint Cognitive Human Machine Systems

IFATCA JCHMS GROUP

Version 6.1
12/3/2024

Contents

Editorial

Today's Air Traffic Management (ATM) system is heavily reliant on the interdependence between designers, technology, and the human operator. Although there have been several periods of time where the demise of the human operator has been predicted, it hasn't materialized. Especially in Europe, recent discussions, have created a push for a change of the role of the human operator. It seems that a system where the human operator is no longer necessary is attractive and is promoted by many stakeholders. The push and political agenda will probably continue to favour the notion of full automation as defined in the many different descriptions of automation. Even if this push does not result in full automation, then there is at least the expectation that human operators will have to move from a control position into a monitoring or managing position, thus demanding that the human operators introduce new competencies and skills. Despite the attractiveness of eliminating human operators, this is simply not feasible in the overall aviation system and any attempt to remove human operators may increase their importance because of the adaptability and creativity that humans bring and automation lacks.

There is an alternative to this approach and underlying philosophy of automation. An approach where it's important to try to understand the totality of the system before we try to change the parts within the system. It assumes that the Aviation system is a complex system that is dynamic, adaptive, and evolving and where context, self-organisation and emergence are always present. Taking this view leads us to a different path for designing today's aviation system. This approach is based on non-linearity, circular design, and the understanding of how the parts relate to each other reflects the centrality of a system's approach to design and operation in the Joint Cognitive Human Machine (JCHMS) narrative.

IFATCA believes that ATM systems' performance can be optimized by designing and integrating technology into the equation adopting the path of Joint Cognitive Human Machine System (JCHMS) and finding new ways to establish an ecosystem where technology, designers and human operators coexist.

The narrative that failure is either due to human or technical failure has been governing development of the aviation system for a long time. IFATCA believes that technology is built and used by humans and therefore the notion of either technological or human failure doesn't make sense. It's all human failure, it's just a matter of apportioning responsibility between humans.

Staying in control is important. The implementation of Artificial Intelligence (AI) and Machine Learning (ML) will introduce new uncertainties that may reduce the control that we have This challenge needs to be dealt with, and we believe that applying the notion of JCHMS can help address it.

IFATCA's view on how to design and integrate new technology in ATM includes the following assumptions:

- The more advanced a control system is the more crucial the contribution of the human operator will be (Bainbridge, 1983).
- We need technology that makes us smarter – not smarter technology.
- New technology needs to be designed by designers and operators with overall system goals in mind.

There is a need to move towards a joint 'thinking' model, where the joint system comprising the designer, the technology and the human operator is the model for future technological solutions. The joint view aims to combine the strengths of humans and technology so that they amplify each other, the ability to respond and anticipate surprises is increased and overall system performance is improved. For IFATCA it's paramount that we build on the successes of the past. Within IFATCA, "operational controllers" are working hard to ensure that the operational voice is heard at the highest level in ICAO – the Air Navigation Commission – through regional planning and implementation groups into regional activities.

Changes in the ATM domain and at the ATM/CNS front are of a re-occurring nature and challenges of research, development, and transition to introduce these changes are daily life for ANSPs and their Staff. Be it Air Traffic Controllers, Technicians, Engineers, Managers and Decision Makers. New Technologies leading to digitization or digitalization, including Artificial Intelligence (AI) and Machine Learning (ML) are finding their way into the ATM working environment.

The introduction of new technology will have to be done in the context of a live operational ATM system, where minimum service provision will have to continue being provided even during the transition period. Moreover, linked to the regulatory and certification challenges, a lot of the new technology will have to be interwoven into the existing architecture, which will create new challenges, and surprises will not escape the rough journey of innovating technological systems in ATM. Human operators will be needed to solve the challenges associated with these surprises.

Air Traffic Controllers are at the front when it comes to using new equipment. Their daily working environment is one of constant change, therefore IFATCA continues to develop guidance, information, and educational material regarding new technologies, be it increased automation of the housekeeping tasks or a digitized working environment. In order to carry out this challenging task, IFATCA has created a team called the Joint Cognitive Human Machine System (JCHMS) group, which has produced this paper.

We try to explain further and elaborate on the concept of the JCHMS.

This paper is structured as follows:

After a general description of why a paper such as this is necessary (Chapter 1), readers will find a chapter that elaborates on how we can reduce the gap between designers and users (Chapter 2) and the final chapter (Chapter 3) explains the fundamental challenges of introducing AI in the ATM

As annexes, you will find a primer on Cognitive Systems Engineering (CSE), as well as other helpful reference documents.

- If you are an Air Traffic Controller, you will find very helpful guidance material, trying to educate and make sense of the needed changes and how they can be integrated and embraced in an operational environment. For a reflective Air Traffic Controller, chapters 1 and 2 will be most useful although reading of the whole document is strongly advised.
- If you are an ATM Manager who is responsible for any kind of change management, you will find a better understanding of what is at hand and can learn how to avoid errors from the past when relying on new research or solutions proposed from the drawing board. It will assist you to de-risk the change management process. Chapters 1, 2 and 3 will be an ideal reading.
- If you are a Decision Maker at the ANSP level, you will be able to use this document to better understand the complexity of introducing new technology in a perfectly running system. Chapters 1, 3 and 4 will be an ideal reading.
- If you are a member of the Engineering Community, be it a design or safety engineer, human factors or system engineer, this document will find that all chapters should be relevant.
- If you are part of the Research Community, you might be inspired to push for more applied research based on some of the proposals made in the paper. All chapters should be relevant.

1. Towards an Adaptive Human Systems Integration

1.1. Introduction

It is paramount for our approach to improving and maintaining the performance of the aviation system that we look at how we understand the system and the processes that are at the core of the aviation system. In this chapter, we present our understanding of both the processes that characterise ATM operations as well as the technical solutions proposed to augment and improve these. We contrast these with what we call the current paradigm. Our view consists of some fundamental changes, a mind-set change it is argued, to how many people think about design, organisations, humans, and machines (technology).

As an introduction to the mind-set change that we envisage, the table below highlights some of the myths perceived around the extant philosophy of new technology (Table 1-1):

Assumed Benefits	**Real Complexity**
Increased performance is obtained from "substitution" of machine activity for human activity.	Practice is transformed; the roles of people change; old and sometimes beloved habits and familiar features are altered—the envisioned world problem.
Frees up human by offloading work to the machine.	Creates new kinds of cognitive work for the human, often at the wrong times; every automation advance will be exploited to require people to do more, do it faster, or in more complex ways—the law of stretched systems.
Frees up limited attention by focusing someone on the correct answer.	Creates more threads to track; makes it harder for people to remain aware of and Integrate all of the activities and changes around them—with coordination costs, continuously.
Less human knowledge is required.	New knowledge and skill demands are imposed on the human and the human might no longer have a sufficient context to make decisions, because they have been left out of the loop, automation surprise.
Agent will function autonomously.	Team play with people and other agents is critical to success—principles of interdependence.
Same feedback to human will be required.	New levels and types of feedback are needed to support peoples' new roles—with coordination costs, continuously.
Agent enables more flexibility to the system in a generic way.	Resulting explosion of features, options, and modes creates new demands, types of errors, and paths toward failure—automation surprises.
Human errors are reduced.	Both agents and people are fallible; new problems are associated with human-agent coordination breakdowns; agents now obscure information necessary for human decision making—principles of complexity.

Table. Putative /assumed benefits of automation versus actual experience. (Bradshaw et al. 2013)

Table 0-1: Myths about assumed benefits of Technology.

We would like to explore the fundamental change from the current paradigm to the joint view through the following questions/statements:

- Separate or Joint – The current paradigm and the joint view?
- Increasing complexity, uncertainty, and surprises.
- Staying in control.
- Technology is also humans – the integrated view.
    - Controllers, designers, and engineers not only use the technology; they are the technology!
- Automation – What does it mean?
    - The left-over strategy.
    - People are the technology.
- Responsibility and the consequences of the paradigm change.
    - How we treat the human in general.
- The radical change doesn't mean that we can't increase the use of technology. It is about looking at the world through a different lens.
- The efficiency and sustained adaptability trade-off.
- Control and adaptability.

1.2. Automation – What Does It Mean?

The language that surrounds automation can, and does, polarize opinions and perceptions. Language is important as it shapes positions and creates views around concepts and plans for changes in working environments and routines. These then become the drivers of expectations.

The term 'automation' has very specific meanings to different stakeholders and actors. From this flow different understandings of how automation is conceived and what objectives any design and implementation can be achieved, as well as drives views of what the implications and consequences may be.

The engineering community may conceive 'automation' in ways that are akin to the philosophy of automatic control: a means to achieve reliable, efficient, effective, and predictable performance without operator participation. Automation in this sense is a notion that conceives technology as a means of achieving consistent and repeatable system behaviour.

A perspective that reflects another view is that of Paul Fitts. The Fitts List, devised by Paul Fitts in 1951, is grounded in an examination of the respective capabilities and limitations of the human and machines in the future human engineering for an effective air-navigation and traffic control system (Fitts, 1991). In a section entitled Men versus Machine (mindful that it was conceived and written in 1951) presents two views of the abilities of humans and machines. Fitts observes that one of the greater advantages of including human elements in a system is increased flexibility (Fitts, 1951, page 7) and that 'it is probably a good plan to let human beings play an important role in the system'.

What does this mean for 'automation' in the widely held view of the term? There are alternative views.

Boy, (Boy, 2020) identifies three design processes that shape different human-systems integration:

- Substitution: In this characterisation of automation, human functions are replaced with machine functions – hence substitution.
- Amplification: amplifying those functions employing specific machine functions and vice versa as a design strategy to enable the human to be actively involved in the activity jointly.
- Speculation: the design of human-systems integration which enhances human capabilities through machine functions designed to enable this. Emerging new human functions will be discovered that will lead to new dimensions and tasks to be integrated into the joint human-agent systems.

The term automation in these latter two contexts does not fit with the essence of the text above. At one level the design choices and processes have evolved from substitution of the operator, to recognizing that the operator can bring specific attributes that are necessary – as they were in 1951 as much as they were in 2014 and Winter's conclusion that Fitts lays the foundations for the critique of automation and substitution of the human. Leading to the current view, that emerging human functions will be discovered as human systems integration becomes deeper. This is contra to the often cited view of automation, as well as the rationale for ever greater deployment and implementation of automation.

Fitts's arguments, which Winter cites (Winter, 2014), in the report, concluded: 'Human tasks should provide activity. The roles of the human operators in the future air navigation and traffic control system should be active rather than passive ones' (Winter, 2014, p.).

Perhaps too, it is relevant to recognise Fitts's observations, again in 1951, on what was to become introduced by Bainbridge as the ironies of automation: human operators' practical skill and long-term knowledge eventual degradation. Recent discussion about the Ironies of Automation confirms their relevance in 2024.

The language that can be found in this context both disturbs as well as reassures.

In Fitts's paper, there can be obtained a view of function allocation within social-technical systems. Which leads to a train of arguments around how human and machine function together – independent actors? A form of team? Or as a form of joint activity?

Boy uses a different language to characterise the activity that is intrinsic when considering the term automation. To orchestrate or to choreograph the allocation of functions, (which is what Fitts introduced in 1951 – function allocation), using a model – the orchestra model – to transfer specific cognitive functions from human to machine agents. This approach recognises that the 'multiple transfer of several cognitive functions from several human beings to several machines (Boy, 2013, pg 11-12) induces greater complication and complexity to the 'automation' of work systems'.

This is introduced in, for example, the work of Klein and Bradshaw (Klein 2016; Bradshaw, 2011). Fundamental to understanding the argument, is the realisation that merely transferring a function or task is not the complete nature of the design nor does it complete a design. The outcome can be a partial design solution as the fuller context has not been fully understood. Dimensions such as responsibility and interpretability for example, as perspectives of the substitution of functions and tasks of human agents with machine agents that now gain critical importance.

What becomes evident is that automation, as commonly understood in a 'folk' sense presumes discreet functioning of the human and machine agent. The reality is very different. New technology changes the nature of the tasks of work itself. Machine and human agents are considered not so much as independent agents, but as sharing functions and tasks with the human in control. This transforms the nature of the term automation. Less the transfer of functions between human and machine agents, but the nature of sharing functions in joint activity. Work itself in this view is categorized as macro-cognitive work.

The classic language and expectations of automation are in practice transcended by joint cognitive systems and macro-cognitive work systems.

IFATCA believes that automation can only exist if you can fully control the context or the input to the system, regardless of whether it is done by a human designer in any of the development stages or the human operator working with the system either independently or with technology assistance. And because full control of all variables is not possible in the aviation system, there will always be a need for the emphasis on joint thinking much more than there is a need for separated or sequential thinking. If we look at the model called COCOM that Hollnagel and Woods presented in the late 90s, we are presented with a cyclical view that never starts and never stops. Hollnagel and Woods argue that:

- Actions should be seen together (the performance of the whole rather than its parts).
- Focus on anticipation and response.
- Users are seen as part of the whole.
- The influence of context is direct. The context affects the operator's actions and determines the level of control possible. Higher uncertainty = less control.
- Models are functional rather than structural. The emphasis is on performance rather than on internal processes.

If we consider a common definition of automation in the context of the joint view it will be obvious that the meaning of automation is not so easy to understand and use. If automation means that technology will independently perform a task that was previously performed by a human, it becomes obvious using the joint view that technology cannot exist without some kind of interdependence with its surroundings. It is much more useful to talk about the performance of the joint system (organisations, humans, and technology). We suggest using the word technology instead of automation. Furthermore, we suggest not to use automation taxonomies, automation levels and definitions.

1.3. Separate or Joint – The Current Paradigm and the Joint View?

Today's aviation system consists of many different actors and agents that affect the ability to respond to uncertainty and surprises. For better understanding, IFATCA assumes that there is a basic shared model of operation such as common ground in joint activity (Klein et al, 2005) between different actors. The basic model of operation consists of two interdependent processes (Figure 1-1). One is the process of preparing, the other is the constant real-time adaptive capacity process - that is the capacity to adapt to situational and fundamental surprises (Eisenberg et al, 2019) and performance variability whilst sustaining production and system goals, which practitioners deliver principally.

The process of preparing entails procedures, checklists, runway signs, maps of the air, lightning, technology, the allocation and securing of resources, designing new technology and many other activities. Organisational adaptive capacity is developed through training, experience, the ability of humans to anticipate, pattern recognition, mental models, prioritising, the ability to respond under time pressure and many more skills needed to respond to changes, uncertainty, and surprises that we know will occur.

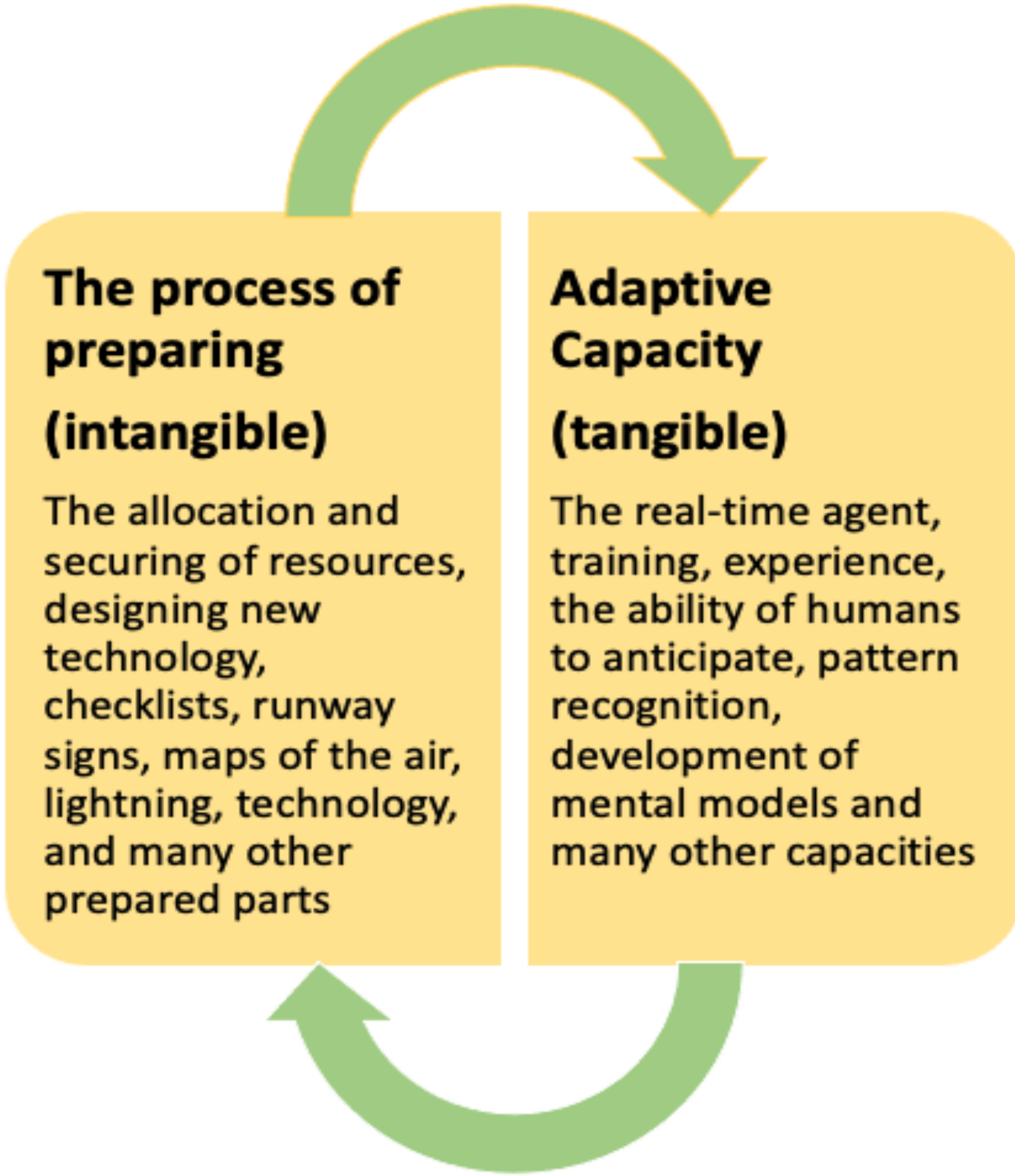


Figure 0-1: The basic model

Designing technology to handle uncertainty and surprises requires that the designers of technology do so with this characteristic of 'work' in mind. To do this, designers need a complete understanding of the uncertainty and surprises that will emerge within the aviation system. However, this requires perfect knowledge. As we all know, perfect knowledge is never available to operators e.g., Air traffic controllers (ATCOs) quite often improvise in situations to meet the challenges of traffic imposed by novel events, unfortunate actions, and shortcomings of the work system. In the ATM system balancing efficiency and thoroughness involves, relying on one's technical skills and professional experience, applying and adapting existing procedures under conditions of time pressure, uncertainty, and high workload. The rapid expansion of information technology has increased the amount of information presented to operators without any assistance in how to make sense of or anticipate the current situation or future trends. Quite frequently, operators are dealing with a complex and dynamic environment that requires them to attend to multiple events, anticipate aircraft conflicts and comprehend or make sense of evolving scenarios.

Experience has shown that staying in control when exposed to surprises is the main challenge in today’s aviation system. Today’s rare accidents are characterised by the complexity and unanticipated consequences of tight couplings rather than by broken parts or components. It is unrealistic to assume that uncertainty and the unanticipated consequences of tight couplings can be eliminated, there will sooner or later be a situation that was not considered when the system was designed. Moreover, even if uncertainty in ATM can be reduced through the means of more rigid procedures, this will inevitably come at the cost of flexibility and efficiency during periods of non-standard circumstances (e.g., heavy weather days).

This leads to a system requirement for designs to have the human operator actively involved in the control functions of the system.

The contrast between the separating view and the joint view has been described by Hollnagel and Woods as interaction with technology or the interface rather than interaction through the interface. There is a significant difference between these two views, and it has implications on how we design, analyse, learn and how we treat humans that work within the system.

Following the description by Hollnagel and Woods, the characteristic of the separate view is that humans and technology work separately and there is no interaction between them. Using this view leads to the use of the term automation or automated. Whereas the joint view, which is what IFATCA is promoting, and it’s an emphasis on functions, where technology, no matter how many processes the technology is performing, e.g., sending estimates or making complicated calculations, and the human can’t be separated. Technology and humans are a function rather than individually separated parts.

1.4. Uncertainty and Surprises Will Always Be an Element of Complex Systems

Complexity research (Flach, 2014; Heylighen, Cilliers & Gershenson 2007, Cilliers, 2000) and the study of chaotic dynamics have demonstrated that uncertainty and surprise are fundamental aspects of the world around us (Eisenberg, Seager, Alderson, 2019; Lanir, 1983). Instead of an ordered system, such as machines, the aviation system is a complex system whose properties emerge from nonlinear interactions of numerous different agents. These interactions, and the interplay between them, create uncertainty and fundamental surprises (Eisenberg, Seager, Alderson, 2019. Woods et al, 2010, Lanir, 1983) which need to be managed in ways where as far as possible lead to being able to stay in control (McDaniel, Jr., Driebe, 2006).

Erik Hollnagel signs his emails with this quote:

'The difference between what you can imagine and what can happen, is larger than you can imagine.'

Based on the experience of thousands of ATCOs and other operators, we believe that this quote is very useful for the organisation and design of today's aviation system. We are good at predicting and we spend a lot of resources on predicting what can happen, but we will never be able to fully predict and anticipate all scenarios. Therefore, we have designed the aviation system to be well prepared through highly qualified experts, human operators, procedures, airspace design, technical support and many other measures that make us able to respond to many situations and manage surprises successfully and safely.

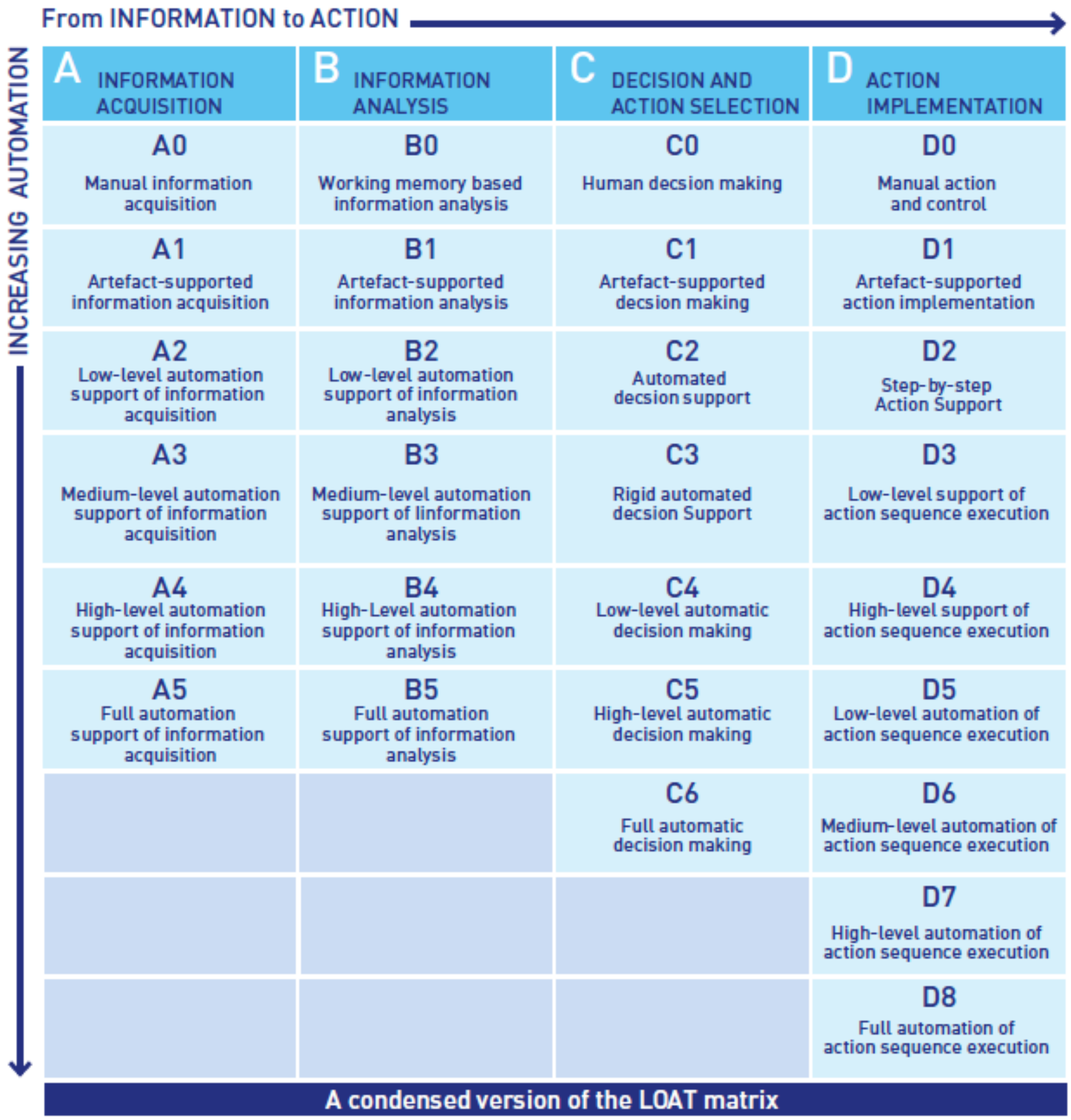
1.5. A New Definition of Levels of Automation

IFATCA suggests that we continue to create joint systems. Based on the ideas of Wiener, Hollnagel, and Woods, to name the most prominent, IFATCA suggests that we take a view that humans and technology will always work together and that the human operator always stays in control.

The joint view changes the emphasis from the interaction between humans and machines to human-technology co-agency or joint agency where one can't be understood without understanding the other.

The consequence of this fundamental change should not be underestimated. If we look at the automation scales that are widely used today, they are mainly based on the idea that humans and machines are considered separately, and the goal is to eliminate the human operator of the system.

One example is the Levels of Automation Taxonomy (LOAT) that was developed within the SESAR project (see Fig. 1-2).



From INFORMATION to ACTION

INCREASING AUTOMATION

A INFORMATION ACQUISITION	B INFORMATION ANALYSIS	C DECISION AND ACTION SELECTION	D ACTION IMPLEMENTATION
A0 Manual information acquisition	B0 Working memory based information analysis	C0 Human decsion making	D0 Manual action and control
A1 Artefact-supported information acquisition	B1 Artefact-supported information analysis	C1 Artefact-supported decsion making	D1 Artefact-supported action implementation
A2 Low-level automation support of information acquisition	B2 Low-level automation support of information analysis	C2 Automated decsion support	D2 Step-by-step Action Support
A3 Medium-level automation support of information acquisition	B3 Medium-level automation support of linformation analysis	C3 Rigid automated decsion Support	D3 Low-level support of action sequence execution
A4 High-level automation support of information acquisition	B4 High-Level automation support of information analysis	C4 Low-level automatic decision making	D4 High-level support of action sequence execution
A5 Full automation support of information acquisition	B5 Full automation support of information analysis	C5 High-level automatic decision making	D5 Low-level automation of action sequence execution
		C6 Full automatic decision making	D6 Medium-level automation of action sequence execution
			D7 High-level automation of action sequence execution
			D8 Full automation of action sequence execution

A condensed version of the LOAT matrix

Figure 0-2: A condensed version of the LOAT matrix (SESAR, 2020)

The difference between the Joint view and the separated view is clear. In LOAT the end goal or the end stage is full automation of the action sequence thereby eliminating the human operator. This means that the designers need to be able to predict all situations that can emerge. It is not clear what action sequence means, but we assume that it sort of accepts that the machine or piece of technology is a part of a system that serves the needs of humans.

If we look at the joint view, the goal is not to eliminate the human, but to create a system where the human (not only the operator) stays in control and is supported by the technology. This also includes AI and ML that will be used to support in achieving the desired result. The joint view aims to combine the strengths of humans and technology so that they amplify each other and that the ability to respond and anticipate surprises is increased.

1.6. Responsibility and the Consequences of the Paradigm Change

Technology has the capability for almost independent action. Despite that, technology will always interact with the human - one way or the other. But no matter the degree of technological independence it is always the human who is responsible and can delegate the responsibility, if the human feels confident that the technology will help achieve the goals pursued. Only humans are held responsible for consequences (that is, only people can act as problem-holders) and only people decide how authority is delegated to technology.

The consequence of the joint view leads to the joint human responsibility for system performance. It is the operator, the supervisor, the designer, the decision maker, politicians, and many other stakeholders that together deliver the performance. Focusing on one stakeholder as the main responsible or influential doesn't make sense in the world of the joint view. The focus is on functions and improving the overall performance, and a consequence of this view is a joint human responsibility. It is our belief that:

It takes teamwork to succeed as well as it takes teamwork to fail.

The radical change does not mean that we cannot increase the use of technology. It is about looking at the world through a different lens.

Taking the joint view is about understanding what has brought about the very reliable and well-functioning system that we have today. Much of the progress we have achieved is achieved because we have been able to build useful technology that enhances the performance (safety and efficiency) of the aviation system. But it is because we have respected the laws of the joint system where the human is the problem holder and where designers, technology and human operators work together to improve performance. It is not because we have substituted the human or achieved level D8 of the LOAT or used the philosophy in the LOAT scheme. It is because we have built technology that allows the human operator to achieve system goals safely and efficiently. Let's not throw the baby out with the bathwater. Let's use the joint view to build our future technology and achieve the improvements that we can accomplish.

‘Combine the strengths of humans and technology so that they amplify each other’

1.7. Staying in control and being prepared to be surprised.

What is meant by loss of control in the context of JCHMS? Hollnagel a Woods (2006) summarised the determinants to stay in control (Fig 1-3).

In aviation, we have always striven for enhanced safety and efficiency by using different strategies. Overcoming the limitations of humans’ natural abilities has been at the forefront of creating well-functioning and safe ways of performing air traffic control. In recent years, many tools that support the cognitive processes of humans have been developed. This has improved, or at least maintained, safety and efficiency and increased the tempo of the ATC system. The technology that has been successfully developed has led to a call for more technology and especially a call for more self-controlling technology, sometimes called automation, replacing the human operator rather than amplifying the abilities of the human operator. But the faster things happen, the more important it is to remain in control.

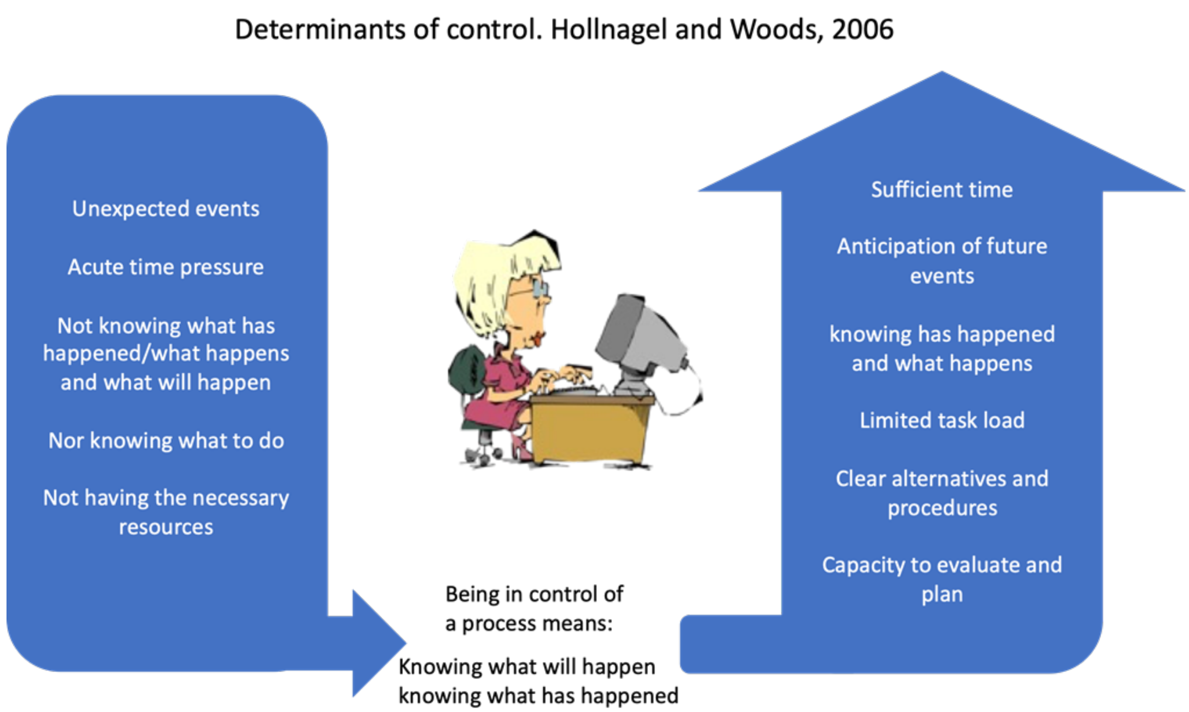


Figure 0-3: Determinants of Control (Hollnagel and Woods, 2006)

A problem with the idea of replacing the human operator is that the designer of advanced technology leaves the operator to do the tasks which the designer can't think how to automate (Bainbridge, 1983). Generating orphan functions – it is also known as the left-over strategy.

This strategy may leave the human operator with the task to act when the technology, or the designers of the technology, give up. This of course is in situations where things usually are complex and there is an urgent need for intervention and understanding of the situation. This will, sooner or later, lead to loss of control, mainly because the human operator is pacified and no longer possesses the ability to meaningfully participate in the recovery of the system. It is stressed here that technology and designers give up not only in emergency situations, but also in tasks that cannot easily be transformed into algorithms. For instance, strategic planning, creative design, moral problem-solving, etc.

Digitalisation relies on highly effective but poorly understood algorithms, and by replacing human functions with technology that is not fully comprehensible, control is gradually and irretrievably lost.

	Left-over principle	**Compensatory principle (Fitts list)**	**Joint Cognitive Human Machine System**
Theoretical perspective	Classic human factors	Human machine interaction (HMI)	Cognitive systems engineering
Function allocation principle	Leave to the operator what can't be done by technology	Avoid excessive demands to human performance	Enhance coagency, support long-term comprehension
Purpose of function allocation	Ensure efficiency by automating whatever is possible	Ensure efficiency of human machine interaction	Enable the JCHMS to maintain control under changing conditions
View of the operator	None	Limited capacity	Interdependence between the human and the machine
System description	Independent entities	HMI	JCHMS
Assumption about interaction	Independent entities	Valid a priori description	Coagency

Table 0-2: Summary of Automation philosophies. (Hollnagel, Woods 2006)

IFATCA suggests that rather than using technology to substitute the human operator we use technology to amplify human abilities and support the human operator in solving problems.

IFATCA proposes that in doing so, the ATM system enhances its resilient performance and capacity to match system complexity.

2. Reducing the Gap Between Designers and Users

2.1. Introduction

This chapter argues that technological designs often underperform compared to the promised benefits delivered. The reason for this is principally because designs have been based on a strategy where practitioners e.g., ATCOs, pilots etc., are expected to take over in abnormal conditions - the so-called 'left-over' design strategy' (Inagaki, 2014, p235). Inagaki also argues, citing Rasmussen & Goodstein, that there is a need to retain the human in the system to 'complete the design, so as to adapt to the situations that designers never anticipated' (Inagaki, 2014, p235). We argue that the need to change this philosophy of design is necessary, as Boy argues: "We cannot think of engineering a design without considering the people and the organisations that go with it" (Boy, 2020). The operating environments of interest here, complex macro-cognitive work designs, are what Boy refers to as socio-cognitive systems (Boy, 2020) and are confronted with the challenge of digitisation and integration of AI.

Within the extant philosophy of the design of future ATM systems and their evolution that exploits technical capability, is a view that there will be a consistent modus operandi for many different and varying system contexts and states. Whilst this is a laudable aim and objective, designs need to be reflected in technical solutions that are context-sensitive – not based on designing out perceived problem facets that only create other problems that change or influence the nature of work and that are not supported by the technical solution.

2.2. Two different mental models

Historically, the aim of designing complex technical systems has been to replace or limit the authority to act of the human practitioner in real-time operational control and management of the system's activities. Another design approach has been to partially remove the human practitioner and create a strict task-sharing environment in which automation deals with routine tasks and events, while the human is exclusively responsible for rare high-complexity situations. In essence, these system activities at the micro level are the work i.e., the purposeful activity of the real-time system. Thus, this perspective of work reduces the purposeful activity as it reduces the involvement of the human practitioner. It reduces the ability to respond to uncertainty and surprise.

This approach is driven by the idea that it is possible to substitute the human practitioner with technology that includes prepared responses to uncertainty and surprises. Lisanne Bainbridge describes this approach, in her 1988 paper (Bainbridge, 1988): The designer's view of the human practitioner may be that the practitioner is unreliable and inefficient, so should be eliminated from the system.

An alternative approach is where systems are designed to be able to support management and adaptation of uncertainty and surprises by collaboration and co-allocation between technology and the human practitioner (Bradshaw, 2011). This approach has been called the Joint Cognitive Approach (JCA) (Hollnagel and Woods, 2005) and is based on the notion that the human practitioner stays in control and that we design for the human practitioner to know what the technology is doing, a design that emphasizes common ground.

Klein extends and amplifies this perspective further in the two views in Table 2-1 below that represent designers' and end users' perspectives:

	Capabilities	Limitations
The designers view	How the system works: by its parts, connections, causal relationships, process and control logic.	How the system fails: Common breakdowns and limitations (e.g., the limitations of the human)
The users view/JCA	How to make the system work: Detecting anomalies, performing workaround and adaptations.	How the users get confused: Complexity and false interpretations.

Table 0-3: Differing design requirements of system designers and system end users (Klein, 2022)

Taking the designer's view there are some caveats that we must be aware of. Again, Bainbridge describes it in this way:

- One, that designer assumptions can be a major source of operating problems and,
- The second problem is that the designer who tries to eliminate the practitioner, the leftover functions, still leaves the practitioner to do the tasks which the designer cannot think how to automate.

- An additional problem is that the most successful automated systems, with a rare need for manual intervention, may need the greatest investment in human practitioner training.

Taking the joint cognitive and the human system integration approaches (Hollnagel, Woods, 2005; Boy, 2020) are extant philosophies for collaboration between technology and the human which retain control in real-time operation.

2.3. Design for collaboration between technology and humans

How do we meaningfully bring technology and social actors – the designer and the user - together to match a complex world with its inherent complex adaptive solutions that are playing out in real–time?

The challenge becomes, in a complex world compared to a complicated world, how do we reconcile the different mental models of the different actors to create designs that enhance adaptive capacity? Figure 2-1.

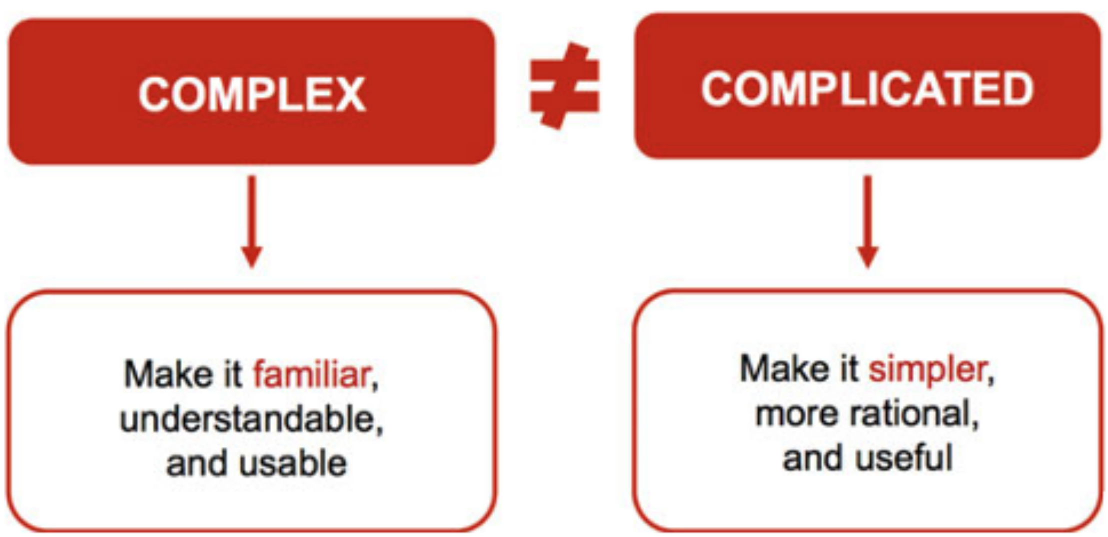


Figure 0-4: The basic model of operation (Boy, 2020)

The dualism of the two different mental models becomes the source of dissonance when considering design and the engineering of the design, for complex socio-technical systems.

Design for complex socio-technical systems, can be seen as an exercise in conflicting value systems (Baxter & Somerville, 2011, citing Land 2009). For example:

- Design values with a fundamental commitment to humanistic principles: the designer aims to improve the quality of working life and job satisfaction of those operating in and with the system.
- Managerial values: the principles of socio-technical design are focused on achieving the company or organisational objectives, especially economic ones.

These two sets of values may be in tension and we argue that this tension can contribute to a decrement in system adaptive capacity as well as adding costs to the system's effectiveness and its ability to achieve system production, goals, and objectives.

One of the driving arguments for automation is that the cost of production is reduced because there are fewer human costs and overheads – this can be associated with training, the reliability of the practitioner is resolved by the deployment of technical artefacts that hold greater reliability, system inefficiencies derived from human the practitioners are alleviated or eliminated through greater deployment of 'automation' as a replacement for the human. Designs that seek to optimise institutional and corporate values and goals, can have the effect - intentional or otherwise -to privilege these objectives and in doing so constrain the design in ways that impact work. The consequences of this are that the practitioners' degrees of freedom are reduced; buffers and margins are impacted in ways that limit the ability of the system to maintain and sustain adaptability when confronted with uncertainty and surprise events and thereby making the system less effective. Additionally, increasing the distance between the practitioner, and the system reduces the practitioner's ability to intervene in case of unexpected events.

Work changes. When work changes there are consequences on the practitioner's ability to create strategies that can exploit system characteristics of agility and flexibility, in other words, adaptive capacity. Boy (Boy, 2020) refers to this as a form of smart integration: designing for innovative complex systems - that exploit the ability to understand increasing complexity. This means embracing complexity. What are we designing for?

A design that embraces complexity will adopt the opposite of the reductionist view – which means reducing or eliminating the effects of complexity, by eliminating or reducing the role of the human. As opposed to designs that embrace and design for complexity by matching emerging system behaviours with creative emergent human real-time responses.

2.4. Conclusion

In this chapter, we argue that we need to move towards designing a socio-cognitive system. This is proposed as a way forward to reduce the distance between practitioners and designers so that designs incorporate joint activity that supports common ground.

To make that possible, we must embrace complexity, uncertainty, and surprises rather than trying to eliminate it. In doing so the role of the human practitioner is recognized and sustained, which permits more efficient and effective operation in real-time. Furthermore, such an approach can lead to maintaining job satisfaction, practitioner involvement and real-time learning and adjustments of patterns of activity associated with complexity, uncertainty and surprises.

One of the means to achieve a constructive approach to the design of effective and meaningful human-system integration is through new ways of working together. These need to be institutionalised and embedded by the Regulator. In the recent Boeing episode, the manufacturer was doing the regulator's job (Nicas, J. et al, 2019).

3. Challenges from the Introduction of Artificial Intelligence

3.1. Introduction

It is widely accepted that a pilot in a cockpit is one of the earliest and most enduring symbols of what we can achieve with a positive and collaborative working relationship between humans and machines. It is also one of the most enduring applications of automation and of what humankind can achieve.

If we go a step further, consider as the unit of analysis the 'air', i.e., the pilots plus flight control and automation, as the (flight) Joint Cognitive System (JCS) then ATM is the environment. It is also possible to go one step further and consider the pilots and the ATM as one system—the traffic flow JCS (Figure 3-1)—in which case the environment is the airlines, the airports, and the other aviation stakeholders (Hollnagel, 2007).

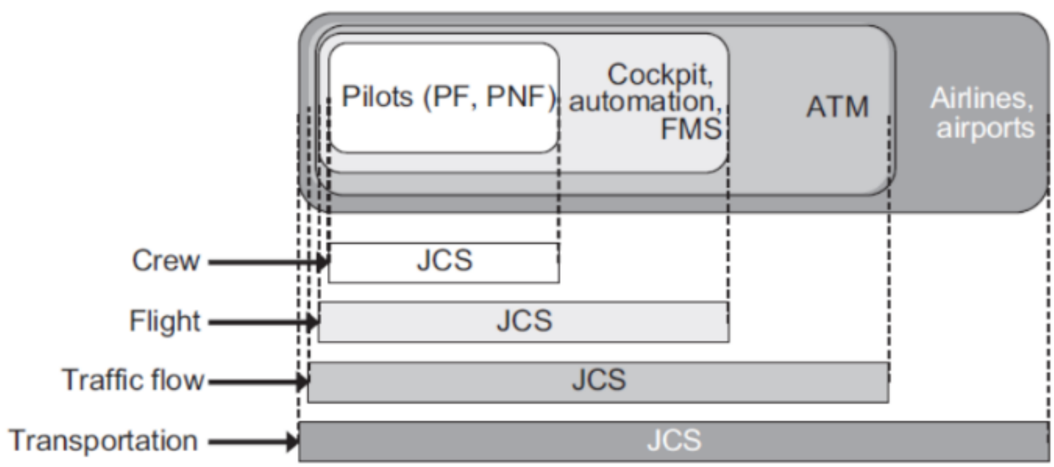


Figure 0-5: The traffic flow Joint Cognitive System (Hollnagel, 2007).

In the era of digitalisation, this traffic flow JCS faces important and potentially disruptive challenges with the introduction of AI both in the air (cockpit technology based on AI) and in the ground components (ATM technology based on AI).

However, innovative technologies not only provide capacity enhancement opportunities and other performance improvements but also raise new regulatory, safety, cognitive and operational challenges, and the need for trade-offs. Therefore, there is an urgent need to examine the introduction of AI cautiously. In this chapter, we present an initial attempt to detect and document the fundamental challenges of implementing AI, in the European ATM system through the lens of Cognitive Systems Engineering (CSE) paradigm (Hollnagel and Woods, 2005; Woods and Hollnagel, 2006).

3.2. Motivation

The significant and continued growth in air traffic in the years before the COVID-19 pandemic has prompted considerable exploration of the use of AI in the ATM. It is expected that AI will provide the additional capacity to meet the challenges of increasing air traffic complexity due to sustained growth and new airspace users and support more efficient and environmentally friendly operations while maintaining and increasing current safety levels.

Modern ATM systems comprise many airspace sectors with varying air traffic flows that interact in complex ways and evolve dynamically. ATM is a work domain that relies on the cognitive functions of Air Traffic Controllers (ATCOs) and their collaboration with flight crews, airport operators, network managers and the other aviation stakeholders to control the airspace, manage safety and adapt to the changing demands of new technological initiatives (Kontogiannis and Malakis, 2017). According to EASA (2021), while the concept of AI has been in existence since the 1950s, its development has significantly accelerated in the last decade due to three factors:

a) significant improvements in the capacity to collect and store massive amounts of data (i.e., Big Data),

b) significant increases in computing power and

c) development of powerful algorithms and methods.

From a purely AI view the ATM system is a real-time safety-critical decision-making process in highly dynamic and stochastic environments where human air traffic controllers monitor and direct many aircraft flying through its designated airspace sectors (Brittain et al, 2020). The extensive introduction of AI is expected to create a new ATM environment, which will be tightly coupled, more complex to cope, with increased air traffic, and pressing needs for

a) minimisation of delays,

b) accommodating a diverse array of autonomous aircraft,

c) operating in adverse weather,

d) smoothing out 4D aircraft trajectories and

e) minimising environmental impact.

AI is expected to increase the resilience and flexibility of the system (i.e., increase support during emergencies in flight or on the ground or unusual situations, as severe weather, failures etc.) and to increase the situational awareness of the operators (e.g., ATCOs and Pilots). In parallel ongoing EASA projects such as Extended Minimum Crew Operations (eMCOs) and Single Pilot Operations (SiPOs) rely heavily on AI and the application of powerful ML methods. eMCOs are defined as operations where the flight time is extended through rest in flight with the minimum flight crew. It is achieved by allowing operations with one pilot at the controls, during the cruise flight phase; however, offering an equivalent overall level of safety through compensation means (e.g., ground assistance, advanced cockpit design with workload alleviation means, pilot incapacitation detection). SiPOs are defined as end-to-end single-pilot operations. Air operations regulation already foresees conditions and limitations under which these types of operations are allowed. In the future, it is expected that these conditions and limitations will need to evolve to extend single-pilot operations to large aeroplanes, if compensation means (e.g., ground assistance, advanced cockpit design with workload alleviation means, capability to cope with pilot incapacitation) are in place to provide for an overall level of safety equivalent to today's two-pilot operations. EASA is working with interested industry stakeholders to explore the feasibility of such operational concepts, while maintaining current safety levels. It is evident that both projects that rely heavily on AI and ML will need ATM support and therefore introduce new operational requirements for the ATC. All these will impose a brand-new array of challenges to the ATM systems in the next 10 to 15 years. In this context, we attempted to elicit and document fundamental challenges to the ATM system from the introduction of AI with the view of drawing attention to the potential side effects that we must act upon promptly.

3.3. How we compiled the list of challenges

We used a range of methods over several phases of fieldwork, documentation analysis and finally divergent thinking, comparative reasoning, and integrative thinking to compile the final list.

In the fieldwork phase, we used many methods. These ranged from participation in structured group discussions (e.g., concerning AI certification) and in-depth discussions (e.g., AI related projects). From a Cognitive Systems Engineering perspective, these techniques belong to the 'natural history' family of methods that are based on a diverse collection of observations in situ (Hoffman and Militello, 2009). This was a recurrent step that was used throughout the whole process. The result of each round was an improved version of the list of fundamental challenges. The next step was to consolidate the list by performing a documentation analysis. During this step, we applied a documentation analysis of the most recent reports, white papers, position papers and technical documents from ATM and aviation organisations (EASA, 2020, 2021; EUROCONTROL, 2021a, 2021b; CANSO, 2021, 2021) regarding digitalisation and AI in the European continent. The next step was to perform a literature review. There is an extensive body of high-quality research in the human factors and CSE literature that can inform the development and application of automated systems. Therefore, we decided to concentrate on some influential research publications and reports in the areas of automation AI, CSE and ATM (Bainbridge, 1983; Parasuraman and Riley, 1997; Dekker and Woods, 1999; Moray and Inagaki, 1999; Parasuraman et al. 2000; Russell et al 2010, Woods and Sarter, 2000; Woods and Branlat, 2010; Woods et al, 2010; Norman, 2013). We also reviewed similar research efforts (Prevot et al. 2012) acceptance of automation studies (Westin, et al. 2016) and introduction of ML techniques that can be used in developing classification rules and eliciting knowledge in the area ATM system (Malakis et al. 2020). Finally, we applied divergent thinking, comparative reasoning, operational expertise, and integrative thinking by capitalizing on the knowledge and operational expertise of the team members through successive rounds of drafting, commenting, and finalizing the list.

In compiling the final list of fundamental challenges, we followed the next principles:

- Fundamental challenges should not be overlapping. To this end, we performed a vertical division into five widely accepted levels in the ATM system, which were identified through the literature review. These levels are:
    - Political / Regulatory.
    - ANSPs / Business.
    - Technical.
    - Operational.
    - Operators i.e. ATCOs.
- Fundamental challenges should not be contradictory. This is a critical requirement as a challenge in one level may be neutral or even beneficial in another.
- Independent of the size, complexity, staffing levels and nature of operations of the ANSPs to which they apply. It is widely accepted that the ATM provision in the European Contingent is fragmented (Finger et al., 2014; Andribet et al., 2022). Therefore, compiling the list having in mind only one or two ANSPs will certainly distort and bias the analysis. To

avoid this, we selected only those challenges that are common for the majority of the European ANSPs.

- Address the European ATM although most of them can be applied to other ATM systems worldwide. European ATM is a unique blend of increased traffic levels, capacity shortfalls, ANSPs fragmentation and complexity among all the worldwide ATM systems. The US ATM system for comparison has an extensive degree of cohesion in terms of ATM provision, CNS systems used, training of operators and centralised oversight. Therefore, we focused only on the European ATM system although quite a few of the challenges may also be valid in other ATM systems worldwide subject to more research.

- Pragmatic in nature. Given the diversity of AI-related projects, there is always the risk that superficial, inconsequential, close to maturity or even remote challenges to be identified. To avoid this trap, we focused only on pragmatic challenges that were uniformly identified and well-understood in nature.

- Not connected to a particular AI paradigm and ML method to the extent possible. There is a plethora of methods, tools, paradigms, and applications with regard to AI and ML (Russell et al, 2010; Barredo Arrieta, 2020). Focusing on a particular method, tool or application would have resulted in a narrow and potentially outdated analysis. For instance, there is a growing literature on the explainability issues of AI (Barredo Arrieta, 2020). Especially for Neural Networks which is the state of the art in Deep Learning. However, focusing only Neural Networks would have restricted our scope into a particular paradigm and method.

3.4. Results

The fundamental challenges from the introduction of AI in the European ATM system are outlined below.

3.4.1. Political / Regulatory

The challenges in the Political / Regulatory area are the following:

- Fragmentation of the European ATM sector (Finger et al., 2014; Andribet et al., 2022).

- Complexity and novelty of AI related products certification.

- Obsolescence of traditional development assurance frameworks that are not adapted to ML and development of the Learning Assurance Concept (EASA, 2021).
- State sovereignty concerns.
- Legal differentiation between Air Traffic Services Providers and ATM Data Service Providers.
- Geographical redundancy and availability of ATM data centres.
- Complexity of agreements on risk sharing and charging mechanisms between States.
- Definition, sharing, and applying a common policy on ethics, related to AI.
- Maintain the credibility and reliability of the ATM systems by promoting social acceptability and change management.
- Build the trust of operators through a system of rules that distribute and clearly define the responsibilities and operating limits of the AI and the operator.

3.4.2. ANSP / Business

The challenges in the ANSP / Business area are the following:

- Organisational transformation issues.
- Insurance and liabilities.
- Constraints from the early adoption of new technology.
- Unclear cost-effectiveness benefits.
- Complexity of service borders and scope definition.
- Costly reinforced cybersecurity infrastructure.
- Complexity of service continuity requirements.
- Disruption of established knowledge sharing, learning procedures, and practices within ANSPs.
- Encourage simulation, training, and feedback paths from operators, to be shared with systems developers.
- Build a new change management policy to gradually drive operators through new technologies and working methods.

3.4.3. Technical

The challenges in the technical area are the following:

- Complexity of sharing of AI infrastructure between countries.
- Extreme dependency of the ML models on the datasets that are used for training, validation, and testing.
- Curse of dimensionality, which refers to the extraordinarily rapid growth of complexity, as the number of variables (or dimensions) increases (Bellman, 1957).
- A significant differentiation of AI solutions for Tower, Approach and Area Control operations.
- Tailor-made AI solutions for each use case that cannot be easily generalised across the same type of units in different geographical areas.
- Consolidation of critical data to guarantee consistency, integrity, and safety of displayed information on the Controllers' Working Positions.
- Develop backup systems to face failures or unusual situations in complex AI systems.
- Define effective AI methods to detect, frame into context, and interpret into decisions weak signals.

3.4.4. Operational

The challenges in this area are the following:

- A scale shift in complexity in terms of the density of interdependencies across processes and activities.
- Synchronization of operational procedures between Air Traffic Services Units (ATSUs) and between ATSUs and the Network Manager.
- Incompatibility with existing Concept of Operations (CONOPS) and the need for the development of new ones.
- Explainability issues of the ML models.
- Function allocation issues. How to make a complex "Blackbox process" visible and understandable to the human operator.

- Develop, validate, and harmonise the integration of AI technologies in the whole system, among all operators (ATCOs, pilots, aerodrome operators and Network Manager).
- Disruption of established relationships, lines of communication and the ability to exert authority.

3.4.5. ATCOs

The challenges in this area are the following:

- Keeping the Operator ‘in the loop’ and situationally aware and able to intervene.
- Disruption of established patterns in coordinated activity between ATCOs’ and between ATCOs’ and flight crews as well as other operators.
- Disruption of established patterns of resilience.
- Increasing instances of automation surprises and clumsiness.
- Increased space for potential and new types of errors that cannot be easily foreseen.
- Demands for new kinds of knowledge and skills.
- Demands for more threads to track that make attention management difficult.
- Demand for the development of new mental models, how the AI system works, how it fails, why it fails, and how to adapt (Borders et al, 2019).
- Operators’ acceptance of their new roles and remits.
- Synchronising an increased number of micro-cultures of ATCOs’ communities which are based on their local practices and local affordances.
- De-Skilling of Operators
- ATCOs’ intervening during failures and contingencies, (Leftover strategies).
- Vigilance/boredom trade-offs.
- Managing of social aspects (e.g., relocation and mobility of Operators).
- Resistance from Operators’ who could legitimately fear for their jobs.

3.5. Discussion

Although the pandemic of Covid-19 significantly decreased the number of flights by slowing down the air transportation system in 2020 and 2021, this is not going to be a permanent situation. Commercial aviation already shows a significant rebound. The ATM systems are operating at its usual high traffic levels and the need for the introduction of AI in the ATM will gain momentum. AI is promising cost reduction, flight efficiency, improved strategic planning, enhanced trajectory prediction, and fuel efficiency to name but a few. However, it is evident from the challenges above that many difficult-to-tackle challenges emerge. The range of challenges that were identified previously may well be the enablers of following safety and performance-related patterns.

3.5.1. Difficult Organisational and Operational Dilemmas

Operations rooms are hectic workplaces, and in many cases, work demands exceed resources, so Operators must do their best and manage their traffic by adjusting their practices to meet existing conditions. In this sense, they are trying to maintain a continuous balance between demands and resources. Moreover, this does not only concern high workload situations, but also low workload periods, during which Operators need to maintain their performance and awareness levels despite not having enough to do to keep them engaged. The effort to tailor human performance to work demands can be described as if it involved a trade-off between efficiency and thoroughness. This view has received particular emphasis from Hollnagel's (2009) proposition of the Efficiency-Thoroughness Trade-Off (ETTO) principle. To cater for efficiency, Operators generally try to achieve their goals by keeping their efforts and resources (for example workload) as low as possible. Safety, on the other hand, requires that more resources are spent on ensuring that the necessary conditions are in place, so that performance goals are achieved without risks. Safety implies that Operators spend more time thinking whether preconditions for an activity are met, execution conditions are right and preparations for contingencies are made in advance. Operators must reach both their safety and performance goals, neither of which should be achieved at the expense of others. The ETTO principle can be viewed also as a trade-off between efficiency and thoroughness that must be balanced even if focused on safety (and not on productivity). This is because sometimes it is - e.g. - necessary to decide quickly rather than thoroughly to maintain safety (e.g. in an emergency, when a thorough analysis would take too much time). In this line of reasoning, unresolved challenges from AI projects will most certainly disrupt this fragile balance and create room for new and more complex dilemmas. Additionally, a very thorough investigation will be required to determine how many, and which ATCO tasks will AI take over and/or assist with. For example, completing the simple and routine tasks would be beneficial in a high workload situation, as this would allow Operators to focus on the complex tasks, but detrimental in a low workload situation, as it would even furthermore reduce Operators engagement and could lead to reduced situational awareness and performance levels. It is stressed here that this is a well-known problem addressed by adaptive automation. AI is aimed to benefit from adaptive functions and maybe this problem will be resolved.

Current safety methodologies cannot cope well with AI-related projects especially when it comes to learning assurance (EASA, 2020, 2021). EASA developed a multi-year project to address exactly this type of weakness in certification. ANSPs' safety methodologies focus on the needs of single agents, but do not allow risks of different types and sources to be assessed with reference to each other, singly or in combination in dynamic environments. Hence, dysfunctional interactions arise that are beyond the control of single agents and current methodologies cannot adequately deal with them.

3.5.2. Transform or Transfer Hazards to Other Stakeholders

In many cases, risks may be transformed or transferred among ATM stakeholders since the solution to one's own concerns may create problems elsewhere. For instance, adverse weather is a safety hazard for all flight operations. When weather cells are encountered, flight crews may request to circumnavigate cells which could increase traffic complexity for Operators, particularly in congested airspaces. Hence, granting a cell circumvention to aircrews may increase the risk of separation minimum infringement and reduce the margin of manoeuvre for controllers. On the contrary, flight operation hazards are effectively reduced. The increase in air traffic complexity (e.g., more conflict points) as several air crews are requiring changes to their routes to circumvent the weather cell cannot always be mitigated by ATFCM restrictions alone. Corver and Grote (2016) showed that area controllers, in addition to reducing and acknowledging uncertainty, may deliberately increase uncertainty to increase flexibility for other actors in the system to meet their operational goals. On severe weather days, Operators often forgo a few procedures, e.g., coordination requirements, to increase their overall efficiency in handling the complex traffic and to ensure the safety of the aircraft. These results are particularly important as uncertainty is likely to increase in future AI-supported operations of area control ATC especially since the explanation of such issues will remain an issue (Barredo Arrieta, 2020). Therefore, risk transferability between ATM stakeholders which is common now and, in a sense, understood (because work practices are built upon it) will most probably be disrupted with unwanted safety and performance consequences. For this reason, any AI that is introduced in ATC must be modelled in a way that matches the ATCO working practice and culture.

3.5.3. Patterns of Events That Are Difficult to Anticipate, Monitor or Comprehend

Complex aviation systems require pilots and controllers to anticipate critical events and stay ahead of traffic so that they get prepared for new evolving situations. For instance, severe weather conditions such as TSRA or microbursts/wind shear are too complex to be fully predicted in their dimensions. For this reason, the set capacity values for a specific sector are often lower than the actual capacity. In fact, many automated support tools have been designed to allow practitioners to foresee the evolution of weather and traffic, which then gives information on whether a sector would become overloaded and whether the gap between set capacity value and actual capacity will be filled. Anticipation of evolving traffic becomes very important since traffic patterns may be affected by factors controlled by different ATM stakeholders (e.g., airlines, airports and ANSPs). With the introduction of AI in the air and on the ground new patterns of events that are difficult to anticipate, monitor or comprehend will materialise. In addition to preparing and updating the currently existing contingency plans, consideration will also have to be made towards potential AI-related issues. This will certainly entail implications for the safety, performance, and capacity of the ATM system.

3.6. Conclusion

There are a lot of questions to be answered in those five levels we identified, with the most critical being at the Operators level. This is a first step towards this goal of raising awareness of challenges raised by the introduction of AI in the European ATM system. It is widely accepted that each technology shift—as the wide-scale introduction of AI in the ATM —extends the range of potential control. In doing so it also extends the range of potential control of the JCS that performs the work as well. Woods and Branlat (2010) framed these challenges in the form of two simple questions: What does it now mean to be 'in control'? How to amplify control within the new range of possibilities. We argue that the way forward in answering the challenges that we have documented above includes the provision of definitive answers to these questions.

4. Integrated Work in the ATC Operations Room – Joint Cognitive Systems in the Wild

4.1. Introduction

This guide was written to help Air Traffic Controllers, Operational Supervisors, Flow Controllers and Flight Information Officers integrate technology in the various forms of new intelligent, autonomous systems, automation and AI/ML that work in partnership with the human operator in the operations rooms. With increased complexity, automation, AI, autonomy of systems, unmanned vehicles, and cognitive assistance, it is critically important to provide Cognitive Systems Engineering guidance on human-machine teaming (HMT).

In our approach, Technology is a collective noun meaning various intelligent systems, automation, autonomous systems, AI and ML systems and cognitive assistants.

Technology in the OPS rooms should act seamlessly within a human operator's workflow, aiding performance by alerting them about operational situations or operational situations that deviate from normal, suggesting alternative solutions that they may not have considered, autonomously reorganising priorities in response to their changing goals, or other collaborative activities. It is well known that there is a wealth of published guidance on how to support human-machine teaming, but that guidance is rarely used to design operational systems that are fielded in the ATM OPS rooms.

To bridge this gap between operators and developers, the IFATCA JCHMS team surveyed and analysed the existing literature to develop a set of general principles and an iterative process for Human-Machine Teaming in the operations rooms based on the Joint Cognitive Human-Machine Systems (JCHMS) principles. The general principles and the iterative process are evidence-based and address the full spectrum of technology ranging from intelligent systems to automation, AI and cognitive assistants.

The rapid development of technology is creating new opportunities to improve the lives of Air Traffic Controllers, Operational Supervisors, Flow Controllers and Flight Information Officers in the OPS rooms around the world. It is also raising new questions about the best way to build trust, interpretability, explanation, observability and direct ability into these systems in the context of Joint Cognitive Human-Machine Systems. These questions are far from solved, and in fact are active areas of research and development.

We propose a set of generic principles and an iterative process of multiple steps before fielding a technology system according to Figure 4-1.

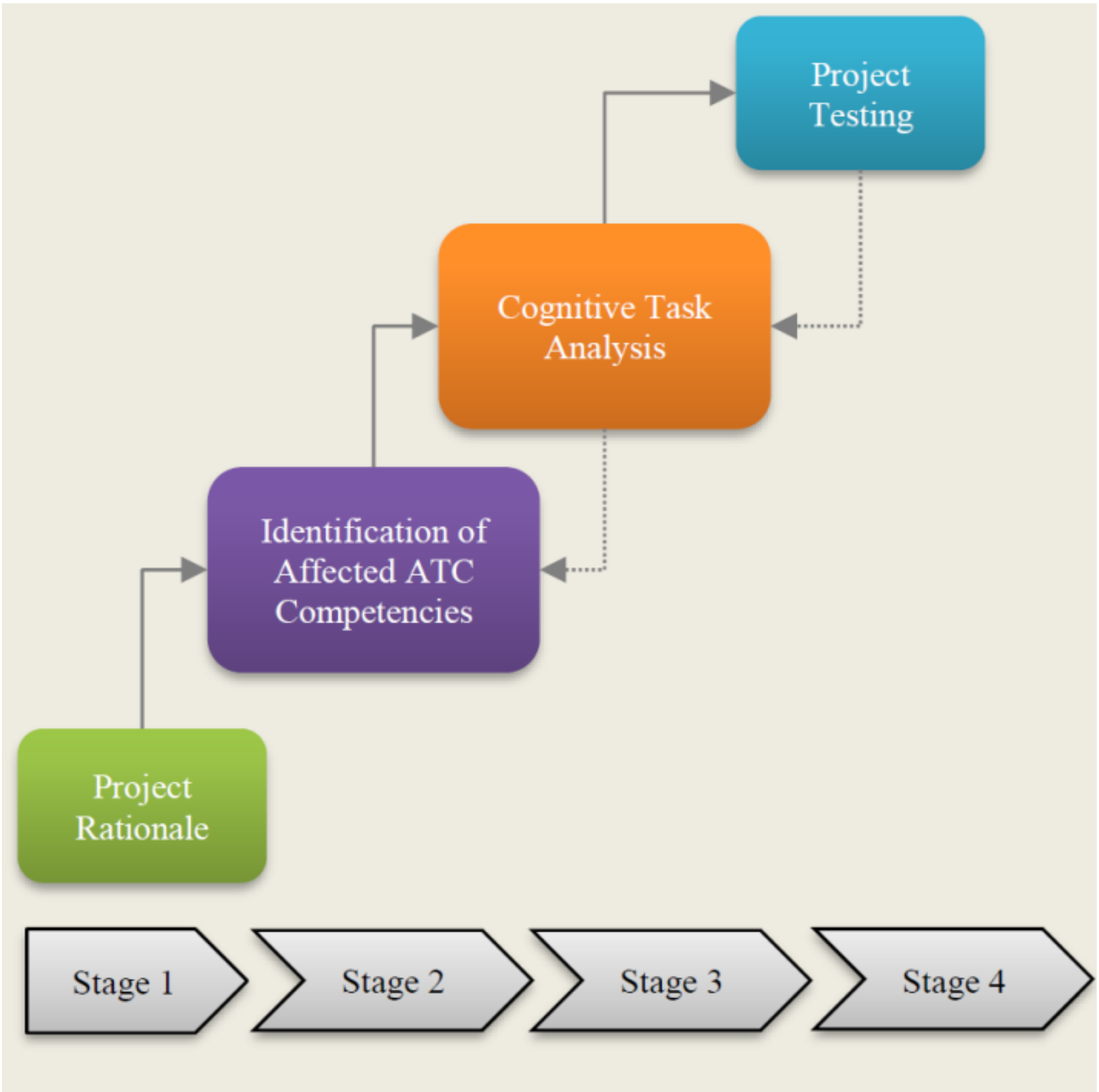


Figure 0-6: The Human Machine Teaming Project implementation steps

4.2. Generic Principles

Reliable and effective operator-centred technology systems should be designed following general best practices, together with practices that address considerations unique to AI, ML, and autonomous systems. Our recommendations are outlined below in the form of nine principles. The first six apply to any technology while the last three apply to AI systems:

1. Focus on designing and delivering operator-centred technology. The way actual users experience the technology system is essential to assessing the true impact of its predictions, recommendations, and decisions in the operational context. Technology design features with appropriate levels of disclosures must be built in. Clarity and control are crucial to an effective operator experience.

2. The trade-off between augmentation and assistance must be carefully balanced. A single answer may be appropriate where there is a high probability that the answer satisfies a diversity of operators and use cases. In other cases, it may be optimal for your system to suggest a few options to the operator. But this must be done carefully as this might cause mental overload in a complex situation, and it goes against the ATCO motto to go back to the basics and keep it simple whenever it gets very busy. Technically, it is much more difficult to achieve good precision at one answer versus precision at a few answers.

3. Aim for a diverse set of operators and use-case scenarios. This will build a rich variety of user perspectives (e.g. age, operational experience, background) into the project and incorporate feedback before (early) and throughout the technology project development.

4. Develop and utilize several technology-specific and operational metrics. The use of several metrics rather than a single one will assist in understanding trade-offs between different kinds of errors and Operators' experiences. Technology-specific metrics must include feedback from user surveys and indicators that track overall system performance both short- and long-term. It is important to ensure that the metrics are appropriate for the operational context and goals of the unit or the Air Navigation Service Provider.

5. Design the technology with the capability to monitor and update the system after deployment. Continued monitoring will ensure any model used takes real-world performance and user feedback into account. Issues with dysfunctional interactions will occur because any model of the world is imperfect almost by definition. Building time into the technology product roadmap to allow addressing emerging and anticipated issues is vital. Trade-offs between short- and long-term solutions to issues must be carefully balanced. Before updating an already deployed model, careful analysis of how the new and deployed models differ, and how the update will affect the overall system safety and user experience.

6. Test the systems in isolation and in cooperation with the other affected systems. Making sure the system is working as intended and can be trusted is essential at the OPS rooms and training facilities. Rigorous unit tests to test each component of the system in isolation and integration tests to understand how individual system components interact with other parts of the overall system are essential. Conducting iterative user testing to incorporate a diverse set of users' needs in the development cycles is also crucial.

4.2.1. AI-specific

The following three principles apply to AI-specific projects:

1. Data Sets (test, training, validation) must be carefully selected, preserved, and utilised. AI and especially ML models are very sensitive and will reflect the data they are trained on. This step includes a list of critical questions that must be answered and a list of considerations to be addressed. The critical questions that must be answered are:

    a. Is the data sampled in a way that represents the users?

    b. Are any features in the model redundant or unnecessary? Using the simplest model that meets the performance goals is the preferred solution.

    c. Are the data biases effectively resolved?

    The list of considerations to be addressed are:

    d. Hyperparameters tuning (e.g., for Neural Networks: Number of layers, number of neurons in each layer, and their connections, selection of the activation functions in each layer, learning rate).

    e. Overfitting.

    f. Avoiding data leakage between training validation and testing data sets.

    g. Removing bad data (e.g., Garbage characters or error codes).

    h. Identifying missing data.

    i. Split test vs cross-validation.

    j. Limit checks (e.g., Range limits, min., and max. values for the parameter).

    k. Consistency checks against the operating design domain (ODD).

    l. Dimensionality reduction.

m. Feature engineering.

n. Normalisation and Standardisation (scaling).

o. Data labelling.

p. Bias management (Bias introduced by any sampling which could be applied to the data, Bias introduced when performing data cleaning or removal of presupposed outliers, recall bias introduced during data annotation or data labelling, Bias introduced by adversarial attack resulting in data poisoning)

q. Capturing Singularities.

r. Selection of the training stopping criterion (criteria) for ML models.

s. Explanatory power of ML models.

2. Understanding the limitations of the datasets and models used. A model trained to detect correlations should not be used to make causal inferences or imply that it can. ML models today are largely a statistical reflection of the patterns of their training data. It is therefore important to communicate the scope and coverage of their training, hence clarifying the capability and limitations of the models to the users. Communication of the limitations of the datasets and models used must be made a top priority in the process.

3. Design early the AI model to be interpretable. Interpretability is crucial to being able to question, understand, and trust AI systems. Understanding complex AI models, such as deep neural networks, can be challenging even for machine learning experts.

4.3. Step 1 – Project Rationale

The first step refers to a list of high-level questions concerning the rationale behind the introduction of the technology project. In other words, these steps address the managerial realities of the project.

It is particularly important that the following set of probe questions are addressed:

1. Has the rationale for the decision to introduce the technology been properly documented?

2. Are we solving the right problem with the right tool?

3. Does the technology display appropriate information to allow operators to meet their performance obligations and their responsibilities?

4. Does the technology provide the operators with the appropriate level of control?

5. Are the human performance expectations and responsibilities clearly identified?

6. How are technology-induced surprises mitigated?

7. What knowledge and skills does the operator need in order to manage the technology in normal and abnormal situations?

8. Are there any unintended adverse effects of the introduction of the technology?

4.4. Step 2 – Identification of the affected ATC competencies

The second step refers to a mapping of the ATC competencies that will be affected by the introduction of the technology.

Here we use the ICAO ATC competencies list for standardisation and familiarisation purposes and identify which of them will be affected and how by the introduction of technology. ICAO defines a list of 10 competencies, each with a range of elements and each element is further decomposed into observable behaviours. These represent knowledge which is: objective, rational, technical, structured, fixed content, context-independent, externalised, easily documented, easy to codify, easy to share, easily transferred/taught/learned, and exists in high volumes.

1. Situational Awareness - Comprehend the current operational situation and anticipate future events.

    a. Monitor the operational situation.

    b. Scan for specific or new information.

    c. Comprehend the operational situation.

    d. Anticipate the future situation.

    e. Recognise indications of reduced situational awareness.

2. Traffic and Capacity Management - Ensure a safe, orderly and efficient traffic flow and provide essential information on environment and potentially hazardous situations.

    a. Manage traffic situation.

    b. Achieve optimal operational performance.

    c. Disseminate flight information.

    d. Inform pilots of essential traffic and weather information

3. Separation and Conflict Resolution - Manage potential traffic conflicts and maintain separation.

    a. Detect potential traffic conflicts.
    b. Resolve traffic conflicts.
    c. Maintain separation between aircraft.
    d. Maintain separation of aircraft from terrain and known obstacles.

4. Communication - Communicate effectively in all operational situations.

    a. Select appropriate mode of communication.
    b. Demonstrate effective verbal communication.
    c. Demonstrate effective nonverbal communication.
    d. Demonstrate effective written and automated communication.

5. Coordination - Manage coordination between operational positions and with other affected stakeholders.

    a. Determine the need for coordination.
    b. Select appropriate method of coordination.
    c. Perform coordination.

6. Management of Non routine Situations - Detect and respond to emergency and unusual situations related to aircraft operations and manage degraded modes of ATS operation.

    a. Manage emergency and unusual situations related to aircraft operations.
    b. Manage degraded modes of ATS operations.

7. Problem Solving and Decision Making - Find and implement solutions for identified hazards and associated risks.

    a. Determine possible solutions to an identified problem.
    b. Prioritize effectively.
    c. Manage risks effectively.

8. Self-Management and Continuous Development - Demonstrate personal attributes that improve performance and maintain an active involvement in self-learning and self-development.

a. Manage stress in an appropriate manner.

b. Self-evaluate to improve performance.

c. Use feedback to improve performance.

d. Adapt to the demands of a situation, as needed.

e. Engage in continuous development activities.

9. Workload Management - Use available resources to prioritize and perform tasks in an efficient and timely manner.

a. Adapt to differing workload conditions.

b. Recognise where and when assistance is needed.

c. Request assistance when and where required.

d. Manage time effectively.

e. Use ATS equipment efficiently and effectively.

10. Teamwork - Operate as a team member.

a. Provides both positive and negative feedback constructively.

b. Accepts both positive and negative feedback objectively.

c. Shows respect and tolerance for other people.

d. Carries out actions and duties in a manner that fosters a team environment.

e. Manages interpersonal conflicts to maintain an effective team environment.

f. Raises relevant concerns in an appropriate manner.

g. Shares experiences with the aim of continuous improvement.

For all these elements, the team has to ask the following question:

To what extent does the technology affect the [name of competency element]?

The rating will follow a Likert five-point scale from -2 up to +2 with -2 corresponding to a strong negative effect 0 to a neutral effect and +2 a strong positive effect. The proposed rating may change but the real problem is who will make the assessment. The ATCOs and their trainers will have the best understanding of the competencies. However the designers will have the best understanding of technology. Human factors engineers may be valuable in the process to bridge the gap between both.

There is a need to recognise operator bias in their assessment, especially if they are not advocates of the implementation of the technology at hand!

4.5. Step 3 - Cognitive Task Analysis

At this step, a Cognitive Task Analysis (CTA) is performed. CTA methods are useful for understanding the task challenges and the cognitive strategies employed by operators to cope with them. It's important to highlight here that the CTA needs to be undertaken by a competent HF professional. There is a need to acknowledge that multiple methods (workshops, observations, testing during simulation) are required to counter the user bias. Users will not always tell you the full story! Also, they sometimes can be unconscionably competent/incompetent

We propose a five-step CTA with some probe questions at each stage:

1. (A)ssessment of the situation—how operators recognise similar situations experienced in the past and how they manage uncertainty to assess new situations.
    a. What features of the situation should be recognised?
    b. What was the most important piece of information?
    c. Any other information that might have been used?
    d. Are cues changing over time or masked?
    e. Were you uncertain, at any stage, about the reliability or relevance of the data?
2. (B)alance of constraints and resources—how operators evaluate difficulties, threats, and constraints imposed by the situation as well as how they use resources and affordances provided in the operating environment (affordance is the perception of what actions the environment offers).
    a. What makes traffic de-confliction difficult?
    b. What strategies and time constraints exist?
    c. What resources are needed? (e.g., tools, procedures, equipment).
    d. What factors can affect the outcome? (e.g., weather, tools).
3. (C)ommunication—how operators communicate information, intentions, and actions to others and how they coordinate with adjacent sectors.

a. When and how much information do you pass on to other colleagues?

b. What subtle signs in communication may indicate problems faced by others?

c. What errors and dependencies can be made in coordination?

d. What sort of proactive information and action can increase coordination?

4. (D)ecision making and planning—how operators make decisions, how they work in smart ways and improvise, how side effects are prevented, and how plans may turn out differently.

   a. What strategies exist that allow you to work in smart ways?

   b. Are there any situations in which the plan of action might have turned out differently?

   c. How can you prevent side effects for your favored plan?

   d. Can you think of examples when you improvised in this task or noticed an opportunity to do something better?

5. (E)rror detection and recovery—how operators make provisions to review their work progress, how they manage to detect errors, and later recover them in a timely fashion.

   a. What errors can be made by novices and experts?

   b. How can you detect errors and recover from them?

Apart from the above, the CTA can be supported by the following questions:

1. What other information would be useful to the operators?
2. Is there a more appropriate form to present the information already used as well as the additional new information?
3. Is it possible to increase the reliability of information?
4. Could the search for information be facilitated, and how?
5. Could the treatment of information be facilitated, and how?
6. Could we provide memory support, and how?
7. Could we facilitate the cognitive strategies carried out, and how?
8. Could we promote and facilitate the use of the most effective diagnosis and decision-making strategies, and how?

9. Could we provide support that would decrease mental workload and mitigate degraded performance, and how?

10. Could we provide support that would decrease human error occurrence, and how?

Steps 2 and 3 are complementary and may run in parallel informing each other.

The knowledge that is elicited during step 3 represents Tacit (implicit) knowledge which is subjective, cognitive, experiential learning, personal, context-sensitive/specific, dynamically created, internalised, difficult to capture and codify, difficult to share, easy to share, has high value, hard to document, hard to transfer/teach/learn and involves a lot of human interpretation.

The third step goes beyond the competent deployment of the necessary skills of the operators and captures the dynamics, nuances, insights, challenges, trade-offs and the stories behind how the work is done in the OPS rooms. In other words, step 3 captures, the work as done while step 2 captures the work as prescribed.

4.6. Step 4 - Testing

At this step testing of the technology is performed before going live to the operations room. This a critical step in which use-case scenarios and real traffic situations have already occurred and are therefore consistent with the test, indicating the need for the scenarios to gradually be brought up to the maximum limit of its capacity. E.g., heavy workload, adverse weather conditions. The aim of this step is to make sure the technology system is working as intended and can be trusted. Iterative user testing is proposed to incorporate a diverse set of users' needs in the development cycles. At this stage integration with other processes may be performed (safety change assessment).

It is acknowledged that sometimes system complexity is exacerbated because of safety case mitigations, where additional procedures or reinforcement of procedures are applied to ensure safety and system operability. Often there are changes applied post-implementation as controllers discover inadequacies or failings not previously considered and what was the "work-around" to overcome these, becomes normal operations – not necessarily as designed. At the JCHMS level of abstraction, humans are in all probability adapting modus operandi to overcome these inadequacies. Or, expressed in another way, as the design changes, the human has the capacity to adapt through control to transform incomplete designs into serviceable systems that deliver the goals and needs of system actors and users.

4.7. Conclusion

Changes in the ATM domain are of a permanent nature and challenges of research, development, and transition to introduce these changes are a daily life for ANSPs and their Staff. Be it Air Traffic Controllers, Technicians, Engineers, managers, and Decision makers. Automation is nothing new in the ATM system. The so-called New Technologies leading digitalisation, including AI and ML are finding their way into the ATM working environment. Whereas a lot of expectation is linked to a so-called technology hype introduction of new technology will have to follow the path of introducing new technological components into a running ATM system. Linked to the regulatory and certification challenges, a lot of the modern technology will have to be interwoven into the existing architecture and will create new challenges/surprises and will not escape the rough journey of increased automated systems in ATM.

One of the driving arguments for the introduction of new technology is that costs of production are reduced because there are fewer Air Traffic Controllers' costs - be it training, the reliability and inefficiency of the practitioner. In our view the contrary will happen costs will not be reduced but shifted into new fields such as i.e. cybersecurity or human factors training. Designs that seek to optimise managerial values can have the effect - intentional or otherwise – to privilege the managerial objectives and in doing so constrain the humanistic design. The consequences of this are that the practitioner's degrees of freedom are reduced; buffers and margins are impacted in ways that limit the ability of the system to maintain and sustain adaptability when confronted with uncertainty and surprise events thereby making the system less effective (IFATCA JCHMS Group, 2022). Additionally, increasing the distance between the Air Traffic Controllers, and the system reduces the practitioners' ability to intervene in case of unexpected events.

When work changes, as in the case of the introduction of modern technology in the OPS room, there are consequences on the practitioner's ability to create strategies that can exploit system characteristics of agility and flexibility, in other words adaptive capacity. Boy (2020) refers to this as a form of smart integration: designing for innovative complex systems - that exploit the ability to understand increasing complexity. This means embracing complexity. A design that embraces complexity will adopt the opposite of the reductionist view – which means reducing or eliminating the effects of complexity, by eliminating or reducing the role of the human. As opposed to designs that embrace and design for complexity by matching emerging system behaviours with creative emergent human real-time responses.

The findings of this study are pending further validation and generalisation due to the exploratory character of research. Any associations and inferences drawn from this study are expected to remain relatively stable when studies of introducing new technology to OPS rooms are carried out in live settings. It is also hoped that this HMT framework of principled processes could provide a viable solution to the efficient introduction of innovative technology in the OPS rooms.

5. Appendices

5.1. Introduction

This section serves as a primer on CSE. It is stressed here that the JCHM principles are based on the foundations of CSE.

5.2. Fundamental Concepts of CSE (Woods and Hollnagel, 2006)

- **Cognitive System:** A cognitive system is a system that can modify its behaviour on the basis of experience so as to achieve specific antientropic ends.
- **Demands:** Demands are general aspects of situations that make goal achievement difficult. Demands are seen in the difficulties that arise as situations unfold to challenge the performance of any JCS. Demands are a kind of constraint on how to handle problems. In other words, understanding adaptation depends on understanding the demands adapted to; to see the demands in classes of situations, one must observe processes of adaptation across varying but related contexts. Demands are uncovered (they are not directly visible in practitioner activity) by tracing processes of change and adaptation and settling into equilibria at different scales.
- **Affordances:** An affordance is a relationship between observers or actors and the artefacts used to meet the demands of work. Affordances are about the fit across the triad of demands, agents, and artefacts. Hence, when an artefact provides an affordance, we generally describe a direct mapping or direct correspondence of artefact and demands for a role. When an artefact is poorly designed (results in a poor fit), we generally describe how tasks must be accomplished through an indirect series of steps. The result of such indirect steps is a more effortful, deliberative, or "clumsy" coupling across the triad. Affordances are not properties of artefacts per se; affordances are relationships between an observer/actor and the artefact as it supports the practitioner's activities and goals in context.
- **Coordination:** Coordination and its related labels, collaboration and cooperation, are similarly complex and difficult to define concisely. Coordination points to the basic finding that work always occurs in the context of multiple parties and interests as moments of private cognition punctuate flows of interaction and coordination (Hutchins, 1995). The concept of a JCS

originated as a call to study and design how work is distributed and synchronized over multiple agents and artefacts in pace with changing situations.

5.3. What is Cognitive Systems Engineering (Woods and Hollnagel, 2006)

CSE is a form of systems engineering (Hollnagel & Woods, 1983). Taking a systems perspective has three basic premises.

1. Interactions and emergence: a system's behaviour arises from the relationships and interactions across the parts, and not from individual parts in isolation.
2. Cross-scale interactions (multiple levels of analysis): understanding a system at a particular scale depends on influences from states and dynamics at scales above and below.
3. Perspective: how the parts of a system and levels of analysis are defined is a matter of perspective and purpose.

The unit of interest and analysis in **CSE**, as one perspective on complex systems, is those factors, processes, and relationships that emerge at the intersections of people, technology and work. These emergent processes cannot be seen if one only looks at any one of these alone.

5.4. Laws That Govern Joint Cognitive Systems (JCSs) At Work (Woods and Hollnagel, 2006)

1. **Law of Requisite Variety:** Only variety can destroy variety.
2. **Context conditioned variability:** Skill is the ability to adapt behaviour in changing circumstances to pursue goals.
3. **Law of Stretched Systems:** Every system is stretched to operate at its capacity. As soon as there is some improvement, some new technology, we exploit it to achieve a new intensity and tempo of activity.
4. **Law of Demands:** What makes work difficult, to a first approximation, is likely to make work hard for any **JCS** regardless of the composition of human and/or machine agents.
5. **Law of Fluency:** "Well"-adapted cognitive work occurs with a facility that belies the difficulty of the demands resolved and the dilemmas balanced.
6. **Potential for Surprise:** All **JCSs** are adapted to the potential for surprise in their fields of practice—how do plans survive or fail to survive contact with events?

5.5. Patterns in CSE (Woods and Hollnagel, 2006)

What emerges at the intersections of people, technology and work are:

- **Patterns in coordinated activity**—or its contrast, miscoordination: how cognitive work is distributed and synchronized over multiple agents and artefacts in pace with changing situations.
- **Patterns in resilience**—or its contrast, brittleness: the ability to anticipate and adapt to the potential for surprise and error.
- **Patterns in affordance**—or its contrast, clumsiness: how artefacts support (or hobble) people's natural ability to express forms of expertise in the face of the demands on work.

5.6. Challenges to Inform Design (Woods and Hollnagel, 2006)

- **The leverage problem**—How do studies of JCS at work help decide where to spend limited resources in order to have a significant impact (since all development processes are resource-limited)?
- **The innovation problem**—How do studies of JCS at work support the innovation process (the studies are necessary but not sufficient as a spark for innovation)?
- **The envisioned world problem**—How do the results that characterize cognitive and cooperative activities in the current field of practice inform or apply to the design process since the introduction of new technology will transform the nature of practice? (A kind of moving target difficulty.)
- **The adaptation through use problem**—How does one predict and shape the process of transformation and adaptation that follows technological change?
- **The problem of "error" in design**—Designers' hypotheses, as expressed in artifacts, often fall prey to William James' Psychologist's Fallacy, which is the fallacy of substituting the designer's vision of what the impact of the new technology on cognition and collaboration might be, for empirically based but generalizable findings about the actual effects from the point of view of people working in fields of practice (Woods & Dekker, 2000).

5.7. Over-simplifications (Feltovich, Spiro & Coulson, 1997)

1. **Discreteness/continuity.** Do processes proceed in discernible steps, or are they unbreakable continua? Are attributes adequately describable by a small number of categories (e.g., dichotomous classifications like large/small), or is it necessary to recognize and utilize entire continuous dimensions (e.g., the full dimension of size) or large numbers of categorical distinctions?
2. **Static/dynamic.** Are the important aspects of a situation captured by a fixed "snapshot," or are the critical characteristics captured only by the changes from frame to frame? Are phenomena static and scalar or do they possess dynamic vectorial characteristics?
3. **Sequentiality/simultaneous**. Are processes occurring one at a time, or are multiple processes happening at the same time?
4. **Mechanism/organism.** Are effects traceable to simple and direct causal agents or are they the product of more system-wide functions? Can important and accurate understandings be gained by understanding just parts of the system, or must the entire system be understood for even the parts to be understood well?
5. **Separability/interactiveness.** Do processes occur independently or with only weak interaction, or is there strong interaction and interdependence?
6. **Universality/conditionality**. Do principles hold in much the same way (without the need for substantial modification) across different situations, or is there great context sensitivity in their applicability?
7. **Homogeneity/heterogeneity.** Are components or explanatory schemes uniform (or similar) across a system—or are they diverse?
8. **Regularity/irregularity.** Is a domain characterized by a high degree of routine across cases, or do cases differ considerably from each other even when commonly called by the same name? Are there strong elements of symmetry and repeatable patterns in concepts and phenomena, or is there a prevalence of asymmetry and absence of consistent patterns?
9. **Linearity/nonlinearity.** Are functional relationships linear or nonlinear (i.e., are relationships between input and output variables proportional or nonproportional)? Can a single line of explanation convey a concept or account for a phenomenon, or are multiple and overlapping lines of explanation required for adequate coverage?

10. **Surface/deep.** Are important elements for understanding and for guiding action delineated and apparent on the surface of a situation, or are they more covert, relational, or abstracted?
11. **Single/multiple.** Do elements in a situation afford single (or just a few) interpretations, functional uses, categorizations, and so on, or do they afford many? Are multiple representations required (multiple schemas, analogies, case precedents, etc.)?

5.8. Generic Requirements to Support JCSs that Work (Woods and Hollnagel, 2006)

Support for Observability: feedback that provides insight into a process.

- Integrate data based on a model of the process.
- Align data to reveal patterns and relationships in a process.
- Provide context around details of interest.
- Overcome "keyhole"/extend peripheral awareness.
- See sequence & evolution over time.
- See future activities & contingencies.
- Decompose integrations and inferences into sources, processes, and base evidence.

Support for Directability: the ability to direct/re-direct resources, activities, and priorities as situations change and escalate.

- Anticipation/projection.
- Models of capability.
- Policies for adaptation.
- Intent communication.

Support for Directing Attention: ability to re-orient focus in a changing world.

- Track others' focus of attention.
- Judge interruptibility of others.
- Use Pre-attentive reference.

Support for Shifting Perspectives: contrasting points of view.

- Seeding—structure & kick start initial activity.

- Reminding—suggest other possibilities as activity progresses.
- Critiquing—point out alternatives as activities come to a close.

Definitions

Artificial Intelligence: Technology that appears to emulate human performance typically by learning, coming to its own conclusions, appearing to understand complex content, engaging in natural dialogues with people, enhancing human cognitive performance (also known as cognitive computing) or replacing people on execution of non-routine tasks. Applications include autonomous vehicles, automatic speech recognition and generation, and detection of novel concepts and abstractions (useful for detecting potential new risks and aiding humans to quickly understand very large bodies of ever-changing information). (EASA, 2020).

Competency. A combination of skills, knowledge and attitudes required to perform a task to the prescribed standard. (ICAO, 2017).

Machine Learning: Rooted in statistics and mathematical optimization, machine learning is the ability of computer systems to improve their performance by exposure to data without the need to follow explicitly programmed instructions. Machine learning is a branch of artificial intelligence. (EASA, 2020).

Abbreviations

ACC	Area Control Centres
AI	Artificial Intelligence
ATC	Air Traffic Control
ATM	Air Traffic Management
CNS	Communication Navigation Surveillance
CSE	Cognitive Systems Engineering
CTA	Cognitive Task Analysis
ICAO	International Civil Aviation Organisation
IFATCA	International Federation of Air Traffic Controllers' Association
JCHMS	Joint Cognitive Human-Machine System
LOAT	Levels of Automation Taxonomy
ML	Machine Learning
ODD	Operating Design Domain
OPS	Operations
SESAR	Single European Sky ATM Research

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