Designing Human-Automation Interaction: a new level of Automation Taxonomy

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Abstract

The paper presents a new Level of Automation Taxonomy developed within the SESAR programme to classify and compare different kinds of automation support in Air Traffic Management (ATM). The taxonomy is grounded on the seminal works of Sheridan and Verplanck (1978) acknowledging that automation is not 'all or nothing' and on the framework by Parasuraman, Sheridan, and Wickens (2000) that identifies four generic functions to be supported in a human-machine system (information acquisition, information analysis, decision and action selection, action implementation). Based on other studies, the paper shows how these models are useful to understand the variable nature of automation support, but encounter limitations when identifying distinctive levels to analyse and compare concrete automation examples. Therefore existing automation levels are modified and adapted to the peculiarity of the four functions being confronted with current automation examples in support of both the flight crews' and air traffic controllers' activity. The paper details how the proposed operational criteria can be used to classify existing implementations and derive lessons to improve automation design. Successful experiences of automation in defined operational contexts can be compared with less successful examples, providing insight on how to prevent human performance issues and take full benefit of available technical solutions.

Introduction

With technological evolution, the possibilities for automating tasks of human operators have become more sophisticated as well as the possibilities to improve human-machine performance in complex systems. As postulated in research by Sheridan & Verplanck (1978), automation is not 'all or nothing', that is, automation is not only a matter of either automating a task entirely or not, but to decide on the extent of automating it. Hence, taxonomies of levels of automation for psychomotor and cognitive tasks have been developed throughout the last decades to clarify the range of options between 'automation' and 'no automation'. Other authors (Hollnagel, 1999) have clarified that the decision on what to automate cannot be based simply on a 'Function allocation by substitution'. This approach was applied in the past also by means of the so-called MABA-MABA lists (Men are better at - Machines are better at) (Fitts, 1951). Such lists rely on the idea that, given a set of

In D. de Waard, K. Brookhuis, F. Dehais, C. Weikert, S. Röttger, D. Manzey, S. Biede, F. Reuzeau, and P. Terrier (Eds.) (2012). Human Factors: a view from an integrative perspective. Proceedings HFES Europe Chapter Conference Toulouse. ISBN 978-0-945289-44-9. Available from http://hfes-europe.org

pre-existing tasks, one should decide which ones are worth automating, considering the strengths and weaknesses of respectively humans and machines. Although this approach is now deemed outdated, there is still limited awareness of the fact that introducing automation brings qualitative shifts in the way people practice, rather than mere substitutions of pre-existing human tasks (Dekker & Woods, 2002). The taxonomy proposed in this paper addresses the problem of classifying different levels of automation, also taking into account qualitative shifts and recognizing different ways in which the human performance can be supported by automation.

Background

An initial scale of levels of automation was proposed by Sheridan & Verplanck (1978) representing a continuum of levels between low automation, in which the human performs the task manually, and full automation in which the computer is fully autonomous (cf. Table 1).

Table 1. Levels of automation of Decision and Action Selection (Sheridan & Verplanck, 1978)

Low	1	The computer offers no assistance, human must take all decisions and actions
	2	The computer offers a complete set of decision/action alternatives, or
	3	Narrows the selection down to a few, or
	4	Suggests one alternative, and
	5	Executes that suggestion if the human approves, or
	6	Allows the human a restricted veto time before automatic execution
	7	Executes automatically, then necessarily informs the human, and
	8	Informs the human only if asked, or
	9	Informs the human only if it, the computer, decides to
High	10	The computer decides everything, acts autonomously, ignores the human

A second decisive step was made by Parasuraman, Sheridan, and Wickens (2000) who acknowledged the Sheridan-Verplanck 10-point scale and introduced the idea of associating levels of automation to functions. These functions are based on a four-stage model of human information processing and can be translated into equivalent system functions: (1) information acquisition, (2) information analysis, (3) decision and action selection and (4) action implementation. The four functions can provide an initial categorisation for types of tasks in which automation can support the human.

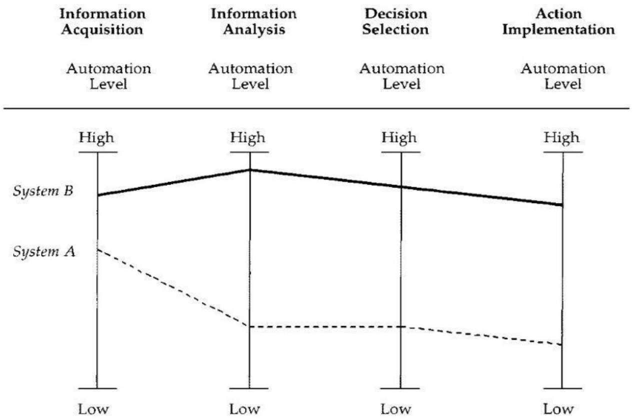

Figure 1. A model for Types and Levels of Automation proposed by Parasuraman, Sheridan and Wickens (2000)

In the same years Endsley & Kaber (1999) formulated a 10-level taxonomy applicable to a wide variety of domains and task types. Their taxonomy covers four generic functions comparable to Parasuraman, Sheridan and Wicken's system functions with each level assigning a function or a combination of functions to either the human or the computer. The list of levels is summarized in table 2.

Table 2. *Levels of automation by Endsley and Kaber (1999) with the corresponding role played by the human and/or computer in each of the four functions*

	Roles			
Level of automation	Monitoring	Generating	Selecting	Implementing
(1) Manual control	Human	Human	Human	Human
(2) Action support	Human/computer	Human	Human	Human/computer
(3) Batch processing	Human/computer	Human	Human	Computer
(4) Shared control	Human/computer	Human/computer	Human	Human/computer
(5) Decision support	Human/computer	Human/computer	Human	Computer
(6) Blended decision making	Human/computer	Human/computer	Human/computer	Computer
(7) Rigid system	Human/computer	Computer	Human	Computer
(8) Automated decision making	Human/computer	Human/computer	Computer	Computer
(9) Supervisory control	Human/computer	Computer	Computer	Computer
(10) Full automation	Computer	Computer	Computer	Computer

Limitations of current models in practical use

The *Model for Types and Levels of Automation* proposed by Parasuraman and colleagues (2000) succeeds in acknowledging the different nature of automation support, as each of the function can be automated to a different level. They also suggest that the scale proposed by Sheridan & Verplanck (1978) is essentially focused on decision and action selection but *can be applied, with some modifications, to the information acquisition, information analysis and action implementation as well, although the number of levels will differ between the stages* (Parasuraman, Sheridan, and Wickens 2000, p. 288). However, after this very promising insight, specific levels for each of the function have not been defined. This has limited the potential use of the model when it comes to providing human factors recommendations in automation design activities. In another study the same authors (Wickens, Mavor, Parasuraman, McGee, 1998) also identified specific categories for the automation of *information acquisition*, but did not go beyond the idea of elaborating different scales for different functions. This provides limited insight on how to manage *information analysis* and how to distinguish *decision and action selection* from *action implementation*.

As a matter of fact when analysing the Sheridan-Verplanck scale (c.f. table 1), one can easily derive that *decision and action selection* and *action implementation* are covered jointly, with the latter appearing only on the fifth level ('Executes that suggestion if the human approves') up to the tenth level ('The computer decides everything and acts autonomously'). From a practical point of view, this categorization sounds reasonable, *i.e.* a tool replacing the human in implementing an action corresponds to a higher level of automation compared to a tool replacing the human only in making decisions. Nevertheless, the scale seems to limit the range of possibilities that can be covered by different automation solutions. For example, if we consider the Traffic Collision Avoidance System (TCAS) currently used onboard aircraft (namely the TCAS II version 7.0) we know that we are dealing with a tool providing a high level of support of *decision and action selection*. In case of imminent risk of mid-air collision, the TCAS triggers an RA (Resolution Advisory), consisting of a specific vertical manoeuvre instructed to the pilot, without leaving room to other options, unless the pilot decides to deliberately override it. The RA provides guidance for the execution of the manoeuvre by visual and aural indications, but does not play a role in implementing the manoeuvre itself that remains up to the flight crew. In this example a high level of automation of *decision and action selection* is associated to a relatively low level of support to *action implementation*. Such combination is difficult to classify according to Sheridan's scale: level 4 'Suggests one alternative' would be considered limitative for the existing TCAS. While level 5 'Suggests one alternative and executes that suggestion if the human approves' would be considered too high, since TCAS does not execute the manoeuvre at all.

Similar problems are faced when dealing with the functions *information acquisition* and *information analysis*. It appears even more difficult to apply the Sheridan-Verplanck scale. As Parasuraman et al. (2000) clarify the scale does not directly apply to functions different from *decision and action selection* and *action implementation*. Therefore any attempt to classify automation for information acquisition and analysis can easily result in illogical or unclear categories.

Different considerations can be made for the scale elaborated by Endsley and Kaber (1999) (cf. previous Figure 2). The main advantage is that all the four functions considered above are covered, named in a slightly different way: *Monitoring, Generating, Selecting, Implementing*. Hence, from a qualitative point of view, the levels of automations are differentiated considering whether the functions are performed respectively by (a) the human, (b) the computer or (c) a combination of the two. In this way the cooperation between human and machine is duly considered, going well beyond the 'all-or-nothing' vision. Nonetheless, when it comes to analysing the automation of each function, there is no way to characterize this cooperation differently. The only alternative is a function accomplished in isolation by either the human or computer, which is too limitative when considering different types of automated solutions. If we take as an example the level 2 in the scale (Action Support), we can see that it is characterized by a *Monitoring* function accomplished by human-computer cooperation. There is no way to distinguish different situations. For example, is the computer visualizing a process that the human cannot see from the distance and the human focusing on the elements of the process that s/he considers more important? Or is the computer also selecting the most relevant elements to visualize and the human just paying attention when these elements are displayed?

Proposal of a new taxonomy

With the attempt to overcome the limitations, a new *Level of Automation Taxonomy (LOAT)* has been formulated. The taxonomy is organized according to the generic functions defined by Parasuraman et al. (2000) and Endsley & Kaber (1999). For each function a specific set of automation levels was developed. Research work from the fields of activity theory and distributed cognition (Nardi, 1996; Hutchins & Klausen, 1996) provided major inspirations to characterize the different levels. The taxonomy was also developed by analysing 26 examples of automated systems (either R&D or operational) and the way they support the performance of either air traffic controllers or pilots.

Table 3 below presents LOAT organised as a matrix with the four functions *(information acquisition, information analysis, decision and action selection, and action implementation)* in horizontal direction. Vertically, each cognitive function groups a number of automation levels (between 5 and 8). All automation levels start with a default level ‘0’ corresponding to manual task accomplishment and increase to full automation. Automation level 1 is based on the principle that the human is accomplishing a task with ‘primitive’ external support, which is not automation as such. Any means that support the human mind, e.g. using flight strips to compare parameters of different aircraft and pre-plan future traffic, could correspond to this intermediate level. From level 2 on upwards, ‘real’ automation is involved.

Table 3. The Level of Automation Taxonomy (LOAT)

A INFORMATION ACQUISITION	B INFORMATION ANALYSIS	C DECISION AND ACTION SELECTION	D ACTION IMPLEMENTATION
A0 Manual Info Acquisition	**B0 Working Memory Based Info Analysis**	**C0 Human Decision Making**	**D0 Manual Action and Control**
The human acquires relevant information on the process s/he is following without using any tool.	The human compares, combines and analyses different information items regarding the status of the process s/he is following by way of mental elaborations. S/he does not use any tool or support external to her/his working memory.	The human generates decision options, selects the appropriate ones and decides all actions to be performed.	The human executes and controls all actions manually.
A1 Artefact-Supported Info Acquisition	**B1 Artefact-Supported Info Analysis**	**C1 Artefact-Supported Decision Making**	**D1 Artefact-Supported Action Implementation**
The human acquires relevant information on the process s/he is following with the support of low-tech non-digital artefacts. *Ex. 1) Identification of aircraft positions on an aerodrome/airport according to Procedural Air Traffic Control rules and without use of radar support.*	The human compares, combines, and analyses different information items regarding the status of the process s/he is following utilising paper or other non-digital artefacts. *Ex. 1) Use of flight strips to compare altitudes/levels/pl. times of different aircraft and to pre-plan future traffic.*	The human generates decision options, selects the appropriate ones and decides all actions to be performed utilising paper or other non-digital artefacts.	The human executes and controls actions with the help of mechanical non-software based tools. *Ex. 1) Use of a hammer or leverage to increase the kinetic energy of human gesture.* *Ex. 2) Use of a mechanical or hydraulic rudder to achieve a change in direction.*
A2 Low-Level Automation Support of Info Acquisition	**B2 Low-Level Automation Support of Info Analysis**	**C2 Automated <u>Decision Support</u>**	**D2 Step-by-step Action Support:**
The system supports the human in acquiring information on the process s/he is following. Filtering and/or highlighting of the most relevant information are up to the human. *Ex. 1) Identification of aircraft positions in the airspace by way of Primary Radar working positions.*	<u>Based on user's request</u>, the system helps the human in comparing, combining and analysing different information items regarding the status of the process being followed. *Ex. 1) Activation by ATCOs of Speed Vectors for specific tracks on the CWP, in order to anticipate potential conflicts in a defined time frame.*	The system proposes one or more decision alternatives to the human, leaving freedom to the human to generate alternative options. The human can select one of the alternatives proposed by the system or her/his own one. *Ex.1) AMAN visualization of the proposed sequence of aircraft.*	The system <u>assists</u> the operator in performing actions by executing part of the action and/or by providing guidance for its execution. However, each action is executed based on <u>human initiative</u> and the human keeps full control of its execution. *Ex. 1) The aural and visual component of TCAS RA in current TCAS II version 7.0 (also LOA C5)*

A3 **Medium-Level Automation Support of Info Acquisition**	B3 **Medium-Level Automation Support of Info Analysis**	C3 **Rigid Automated Decision Support**	D3 **Low-Level Support of Action Sequence Execution**
The system supports the human in acquiring information on the process s/he is following. It helps the human in integrating data coming from different sources and in filtering and/or highlighting the most relevant information items, based on user's settings. *Ex. 1) CWP allowing ATCOs to set flight level filters to display only certain traffic on the screen.*	Based on user's request, the system helps the human in comparing, combining and analysing different information items regarding the status of the process being followed. The system triggers visual and/or aural alerts if the analysis produces results requiring attention by the user. *Ex. 1) ERATO Filtering and What-if function.* *Ex 2). VERA Tool to display the closest point of approach between two aircrafts.*	The system proposes one or more decision alternatives to the human. The human can only select one of the alternatives or ask the system to generate new options.	The system performs automatically a sequence of actions after activation by the human. The human maintains full control of the sequence and can modify or interrupt the sequence during its execution. *Ex. 1) Explicit initiation of an electronic coordination with adjacent sector via digital input (replacing use of telephone).*
A4 **High-Level Automation Support of Info Acquisition**	B4 **High-Level Automation Support of Info Analysis**	C4 **Low-Level Automatic Decision Making**	D4 **High-Level Support of Action Sequence Execution**
The system supports the human in acquiring information on the process s/he is following. The system integrates data coming from different sources and filters and/or highlights the information items which are considered relevant for the user. The criteria for integrating, filtering and highlighting the relevant information are predefined at design level but visible to the user. *Ex.1) D-TAXI tool (including graphical route information)*	The system helps the human in comparing, combining and analysing different information items regarding the status of the process being followed, based on parameters pre-defined by the user. The system triggers visual and/or aural alerts if the analysis produces results requiring attention by the user. *Ex. 1) MTCD visual alerts (allowing some tuning of parameters by the user)*	The system generates options and decides autonomously on the actions to be performed. The human is informed of its decision. *Ex.1) Aural and visual component of TCAS RA in current TCAS II version 7.0 (also LOA D2)*	The system performs automatically a sequence of actions after activation by the human. The human can monitor all the sequence and can interrupt it during its execution. *Ex.1) Acknowledgment by pilot of a clearance received trough CPDLC (data-link) and automatically sent to FMS and autopilot.* *Ex. 2) Autopilot following the FMS trajectory.*

A5 **Full Automation Support of Info Acquisition**	**B5** **Full Automation Support of Info Analysis**	**C5** **High-Level Automatic Decision Making**	**D5** **Low-Level Automation of Action Sequence Execution**
The system supports the human in acquiring info on the process s/he is following. The system integrates data coming from different sources and filters and/or highlights the information items considered relevant for the user. The criteria for integrating, filtering and highlighting are predefined at design level and not visible to the user	The system performs comparisons and analyses of data available on the status of the process being followed based on parameters defined at design level. The system triggers visual and/or aural alerts if the analysis produces results requiring attention by the user. *Ex. 1) STCA visual and aural alerts.*	The system generates options and decides autonomously on the action to be performed. The human is informed of its decision only on request. (Always connected to to an *Action Implementation* level not lower than D5.)	The system initiates and executes automatically a sequence of actions. The human can monitor all the sequence and can modify or interrupt it during its execution. *Ex. 1) Implicit initiation of an electronic co-ordination with adjacent sector as agreed exit conditions (according to Letter of Agreement) cannot be met anymore after changes to the a/c trajectory has been made.*
		C6 **Full Automatic Decision Making**	**D6** **Medium-Level Automation of Action Sequence Execution**
		The system generates options and decides autonomously on the action to be performed without informing the human. (Always connected to an *Action Implementation* level not lower than D5.)	The system initiates and executes automatically a sequence of actions. The human can monitor all the sequence and can interrupt it during its execution. *Ex.1) TCAS AP/FD during a corrective TCAS RA.*
			D7 **High-Level Automation of Action Sequence Execution**
			The system initiates and executes a sequence of actions. The human can only monitor part of it and has limited opportunities to interrupt it.
			D8 **Full Automation of Action Sequence Execution**
			The system initiates and executes a sequence of actions. The human cannot monitor nor interrupt it until the sequence is not terminated.

Principles

The way LOAT is designed demonstrates the following principles:

- An automated system cannot have one ‘overall’ level of automation as such. In other words, a statement about a level of automation for a system always refers to a specific function being supported;
- One automated system can support more than one function, each having a different level of automation;
- The description of each automation level follows the reasoning that automation is addressed in relation to *human performance*, i.e. the automation being analysed is not just a technical improvement but has an impact on how the human is supported in his/her task accomplishment.

It should be kept in mind that these generic functions are a simplification of the many components of human information processing. The functions are not meant to be understood as a strict sequence, but they may temporally overlap in their processing. From a practical point of view, the human may be performing a task that involves one or several functions. However it is useful to differentiate the subtleties between the functions when one wants to identify how a specific automated system supports the human.

Classifying concrete automation examples with LOAT

In an initial validation, LOAT was applied to classify the level of automation of 26 airborne and ground automated systems supporting respectively pilots’ and air traffic controllers’ activities. The first automation examples were used to assess the identified automation levels and to refine the taxonomy. Also, these concrete implementations provided examples for specific automation levels. The full set of examples on Human Performance Automation support was used to perform this preliminary validation (cf. SESAR Joint Undertaking, 2012).

Airborne automation example: TCAS

We analysed the Airbus Auto Pilot/Flight Director (AP/FD) TCAS mode as an onboard example to classify the level of automation. The AP/FD TCAS mode enhances the existing TCAS functionality by implementing a TCAS vertical guidance feature into the Auto Flight computer. Since this innovation represents an increase in the level of automation, it is interesting to compare it with the traditional TCAS functionality in the light of LOAT.

As mentioned earlier, in case of imminent risk of collision, the existing TCAS functionality triggers visual and aural indications to the flight crew to perform an avoiding vertical manoeuvre. The execution of the manoeuvre itself is up to the flight crew. In LOAT terms this corresponds to a level C4 (Low-Level Automatic Decision Making), because the system selects one action and informs the human of its decision. In terms of action implementation, the system only assists the crew in performing the manoeuvre by constantly updating the visual and aural indications until the manoeuvre is completed. And what about the new AP/FD TCAS mode?

The new functionality makes the same kind of decision-making but supports action implementation in a different way. Under the assumption that the Auto Pilot is engaged, the system initiates and executes a sequence of actions to fly the avoidance manoeuvre until the aircraft is clear of conflict. Such automation support corresponds to automation level D6 (Medium-Level Automation of Action Execution). The crew can monitor the sequence of actions by the indications on the Primary Flight Display - and notably the vertical speed indicator - but cannot modify the ongoing action execution. It can be concluded that the adjacent automation level D5 is not applicable. However, the flight crew has the possibility to interrupt the action execution as such and to fly the required avoidance manoeuvre by the conventional procedure, i.e. they can disconnect the Auto Pilot and Flight Director. A further reason that qualifies automation level D6 is that the human can follow the entire action execution on the displays. In turn, this excludes automation level D7 referring to an automation in which the human can only monitor part of the action execution with limited opportunities to interrupt it. In conclusion the analysis reveals that a support in decision and action selection C4 is involved in both cases. However passing from the traditional TCAS to the AP/FD TCAS mode implies a change in action implementation support from level D2 to D6.

Ground automation example: ERATO

An example of ground automation is the ERATO Filtering Function. ERATO stands for En Route Air Traffic Organizer and represents a toolset aimed at supporting the controller in ensuring separation among aircraft in a concerned airspace sector. More specifically the ERATO Filtering Function helps the controller in identifying all the potential intruders of a given flight in the medium-short term (i.e. up to 20 minutes to the predicted conflict). This function is activated on controller's initiative after mouse click on the radar track and allows a quick analysis of an aircraft in its traffic context. In practice, all the track labels of the aircraft that are not in conflict with the aircraft under analysis appear in light grey, while the labels of tracks potentially in conflict convert to a brighter colour. It is worth noting that the system continuously scans potential conflicts but the filtering referring to a specific aircraft and highlighted on the radar screen is only made visible when requested by the controller. In LOAT terms, this qualifies the function as an *Information Analysis* tool at an automation level B3 (*Medium-Level Automation Support of Information Analysis*), because the triggering of a visual alert is implicated, but only after the controller requested the filtering. It is interesting to compare this automated system with other tools playing a similar role in controller's activity. For example other tools in ATM such as the MTCD (Medium Term Conflict Detection Tool) or the TCT (Tactical Controller Tool) are based on a similar logic but can trigger visual alerts advising a risk of conflict independently from any check requested by the controller. Differently from ERATO, these tools represent an automation level B4 (*High-Level Automation Support of Information Analysis*) because they trigger alerts automatically. However, they do not reach level B5 (*Full Automation Support of Information Analysis*) because they allow the user to tune the parameters determining if and when a conflict will be displayed. This is not allowed, for example, in the case of other safety-critical tools in ATM, named *safety nets*. These tools trigger visual and/or aural alerts of imminent conflicts based on design parameters which cannot be manipulated by the controller. It is also worth noting that all the mentioned ground tools represent different levels of support to *information analysis*, however none of them is implicated in *Decision and Action Selection*. In all cases the decision on how to solve the conflict remains completely up to the controller.

The case-by case trade-off to decide for a level of automation

The analysis of human-automation interaction in real situations shows that even automated tools with high technical capabilities may not provide the desired benefit or may be even rejected. It could be the case that the level of automation is either inappropriate or not fit for the specific operational context.

The case of the described controller tools is an example of automation providing real benefits in terms of support to early conflict detection but also disturbances that may jeopardize the controller's performance. The so-called nuisance alerts (i.e. alerts not corresponding to a real safety threat) are a common problem of these tools. When they exceed a certain threshold, it is likely that the controller will decide to ignore or even switch-off the automation. This may become necessary to avoid spending too much effort on checking for the validity of each single alert, at the expense of the usual controlling activity. The nuisance alert can only be minimized when these tools can rely on a sufficiently accurate trajectory prediction. However the quality of trajectory prediction is influenced by various factors that are not exclusively technical. For example airspaces with dense traffic and a lot of ascending and descending aircraft (frequently the case in terminal areas in the vicinity of big airports) are too complex to make the traffic sufficiently predictable. Hence controllers are obliged to provide frequent corrective instructions to aircraft that may not be completely tracked by the automation. In these cases the automation itself makes predictions based on outdated traffic information and may consequently generate nuisance alerts.

Coming back to the ERATO Filtering Function example, such tool may reduce the negative effect of an inaccurate trajectory prediction in a complex airspace, because it leaves the initiative to check traffic conflicts to the controller, offering support only when required. On the other hand tools with a higher level of automation like the MTCD or the TCT may generate an excessive number of nuisance alerts, due to their automatic activation. In the medium and long-term this can cause mistrust in the tools and a tendency to switch them off, which offsets the initial benefit. Nevertheless these tools may offer more protection to the controller in operational situations in which traffic flows are more predictable, ensuring that all conflicts are spotted in a timely manner, also in case of distraction or excessive workload.

Conclusion

This paper presents a level of automation taxonomy which was specifically developed in the ATM context in a SESAR perspective. However, the underlying principles and the description of the LOAT categories are not only applicable in the field of aviation but transferable to other domains in which automation takes place.

The choice of the 'optimal' level of automation in a specific task context is about matching the automation capabilities to a number of operational situations, while increasing the overall performance in efficient human-machine cooperation. Taxonomies of levels of automation have an added value if they become an applicable tool in human-automation design. Such tool should support at least two purposes: (1) support design choices from early design phases on and (2) help to classify already developed automation examples to produce specific human factors recommendations. A prerequisite is that the automation levels are distinctive and that they enable to classify a wide range of concrete automation examples from different domains. LOAT provides specific levels for the different task contexts by addressing four functions. The specific set of automation levels clarifies the 'nuances' of automation enlightening the possibilities in design. The choice of a targeted level of automation can be made explicitly also based on the choice by exclusion, i.e. reflecting on the appropriateness of adjacent automation levels. In the context of evaluating automated systems already in service, one can imagine that a concrete automation is not used as intended or does not fully support the specific operational context. If a potential cause of the problem lies in the underlying automation level, LOAT provides potential alternatives for designing the human-machine interaction by taking full benefit of the technical solution. Cases in which the human may simply switch off or reject automation can be anticipated and mitigated.

Acknowledgement

The presented work was carried out within the SESAR Project 16.5.1 *'Identification and Integration of Automation Related Good Practices'* funded by SESAR Joint Undertaking. The authors contributed to this project under representation of the project members ENAV (by Luca Save, Deep Blue) and Airbus France (by Beatrice Feuerberg, Egis Avia). Further involved project members were EUROCONTROL, DFS, Thales, AENA, and NATMIG. The authors would like to thank Plinio Frasca (ENAV) as well as Sonja Biede-Straussberger and Florence Reuzeau (Airbus) for encouraging this work. A special thank is due to Stefan Tenoort (DFS) for identifying the methodological issue that generated the idea described in this paper and to Christine Maddalena (Egis Avia) for her continuous review and support.

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