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Hierarchical task analysis of current two pilot cockpit operations towards a flexible human-automation task allocation

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***Abstract*—The paper presents a new approach for a hierarchical task analysis. The conducted task analysis is part of developing future advanced assistance and automation systems for small single-piloted high performance and large two-piloted airplanes. The new approach represents a holistic and systemic method for an operational and functional breakdown of a complete flight as well as a coherent linking of operational contexts with aircraft specific operating procedures and concrete atomic functions, i.e., pilot actions and activities. The atomic functions are used as base for a reassessment of current tasks when operating an airplane. The reassessment aims investigating future automation potentials, particularly, a flexible task allocation between pilots and automation. The hierarchical task analysis was performed in the project DARWIN, that is funded by SESAR 3 Joint Undertaking, using the example of the Dassault Falcon 2000EX.**

Keywords—Human Machine Interaction, Human Automation Teaming, Multi Pilot Operation, Single Pilot Operation, Large Airplanes, Small Airplanes, DARWIN

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I. INTRODUCTION

Several automation and assistance systems support pilots conducting safe and efficient flights in commercial air transport operations (CAT). The development of new assistance and automation systems is a continuous process. The SESAR 3 project DARWIN – Digital Assistants for Reducing Workload and Increasing collaboratioN investigates the capabilities of future adaptive human-centered automation [1][2]. This includes the examination and development of more complex, advanced assistance and automation systems (abbr. AAS or automation) allowing a flexible task allocation and flexible task sharing between pilots and automation, e.g., by digital assistants or a digital co-pilot. Flexible task allocation means, that tasks can be executed by an assistance or automation system or a pilot or both in close cooperation. At present, automation and assistance systems support single narrowed functions, but with an increased growing functional extent, interconnections and interoperability. The fundamental question of future developments is, if the tasks currently conducted by pilots might be transferred to specific AAS. The focus hereby lies on the tasks needed and executed when operating small high-performance or large airplanes (CS-23 or CS-25) [3][4]. These tasks comprise all activities and actions performed by pilots plus automation and assistance systems regarding flying, communication, navigation, traffic, weather and terrain avoidance or system management.

The development of new AAS and achieving a flexible task allocation motivated to perform this task analysis. A key requirement for the task analysis was to provide a holistic, complete and concrete base for the reassessment and evaluation, which tasks might be an option to establish more complex and advanced automation as well as which tasks might be unfeasible, too complex or expensive for automation, yet. The assessment primarily addresses the aspect if the capabilities needed to perform more complex tasks, might be implemented and achieved by AAS. Thus, more complex tasks would not be restricted being executed by a pilot. More complex tasks mean, managing an approach and landing including aviating, navigation, communication and system management and not just flying a selected heading, altitude, climb or descent, speed or a cleared route.

Towards a flexible task allocation, the assessment of concrete atomic functions gives an intermediate view, how tasks might be distributed between a pilot and AAS. The task assignment and level of automation will be discussed. The hierarchical task analysis (HTA) was applied using the example of the Dassault Falcon 2000EX, representing a large airplane with a two-pilot cockpit. This aircraft type is operated with avionics of two different avionic suppliers, i.e., Honeywell and Collins Aerospace [5][6]. Both suppliers feature other aircraft types including a steady development and improvement towards new pilot assistance and enhanced automation support.

II. RELATED WORK

The tasks related to the execution of commercial flights with large airplanes were analyzed for different reasons. Task analyses form a common way to face different subjects. The challenge is to find a proper and right approach, out of various task analyses applied. Mostly, task analyses are tailored for the purpose. Additionally, task analyses intent to identify demands and capabilities of human operators needed for human machine interaction or cooperation in order to fulfill a certain task or operation or process [7]. The goal of the new approach is the opposite, to create a starting point for the analysis and investigation of the demands and needed capabilities of future advanced automation, e.g., the accessibility of relevant information, for a shared and common situational awareness or the accessibility of aircraft and avionic systems, system functions and controls.

Task analyses and descriptions can be quite different in target, form, criteria. Neither for the approach nor the description of tasks is a standard available [7]. Miller and Drury worked on the way and manner of performing a task analysis in general [7][8]. The first contribution was published more than 70 years ago. The following publications represent a selection of related work concerning different methods and objectives.

Friedrich et al. for instance generated and published a taxonomy for the tasks operating an Airbus A320 [9]. They investigated and discussed the possible transition from conventionally to remotely piloted airplanes and possible impacts on the function allocation and accessibility of information. The HTA of this work applied the so-called “Social Organization and Co-operation Analysis – Contextual Activity Template” (SOCA-CAT) [10]. The hierarchical approach comprises three layers: 1. focusing on functional purposes, abstract and generalized functions, 2. physical functions and 3. physical form. Concerning the top layer, in a first step, two functional purposes were named, first the safe and second the efficient execution of a commercial flight. In a following step, four abstract functions were identified which are necessary to achieve the two purposes. Each abstract function could be part of the implementation of different purposes. For instance, a safe flight operation contains that the flight parameters have to respect the flight envelope of an aircraft. Furthermore, it has to be ensured that the airplane will be separated from any traffic, terrain and meteorological risk and that the airplane fuel consumption and load plus the aircraft systems are properly managed. The fuel management as well as to follow the flight envelope also implements the functional purpose of conducting a flight most efficiently. In a following step, four generalized functions were identified and assigned to the abstract functions, i.e., aviate, navigate, communicate or manage aircraft systems. The four generalized functions were broken down to 24 physical functions, like managing speed, heading, altitude, flaps and gear as subparts of the generalized function aviate, or position of own ship, other traffic, terrain, meteorological effects, nav aids, airports, runways and taxiways as part of the generalized function navigate. The underlaying physical forms – representing the third layer – contain the following eight items: aircraft controls and systems, aircraft performance, weather, terrain, traffic, airports and its infrastructure, Air Traffic Control Service (ATC) and airspace structure. These physical forms are the basic elements used by the physical functions. The physical functions of this hierarchical approach afterwards were assigned to a flight phase and who executes a function, i.e., the pilot flying (PF) or pilot monitoring (PM) or aircraft’s automation, e.g., the autopilot. The HTA was applied to the approach and landing operation of a large airplane with two pilots. Different levels of automation were also considered, i.e., flying in manual, selected or managed mode. Additionally, the used information was identified and assigned to the former physical functions. Sources of information were measured data from the aircraft and the environment. In a next step, the results of the task analysis for the approach and landing were taken as base for the investigation of single pilot operations (SPO) including a remote pilot. Hereby, the former tasks of the two onboard pilots were reassign to a single pilot onboard and a remote pilot.

Lacabanne and colleagues published the results of another HTA [11]. This task analysis was motivated by the development of a new Flight Management System (FMS). An FMS supports a pilot when flying a planned and cleared route or flight procedures, e.g., departure, arrival, approach and landing. The flight management system also assists the navigation, communication with ATC and fuel management. The focus of the analysis laid on the airplane operation concerning aviate, navigate, communicate and manage systems (ANCM) as introduced by Billings work concerning aviation automation [12]. In order to identify essential functions for the operation of an airplane, seven pilots were interviewed. One specialty was, that the study regarded different types of airplanes – from normal single engine piston airplanes, over complex high-performance multi-engine turbine airplanes to large airplanes and even fighter jets. The task analysis comprised three levels of functions and activities – the first level referred to interfaces, and the last level was linked to related information. The first functional level contained the four domains – ANCM, the second level comprises nine major functions, and the third ten sub-functions. The functional domain Aviate addressed manual and automated flying with respect to the envelope. Navigation focused on the positioning along the flight route from start until destination. The Communication actions regard the communication with ATC as well as among the pilots. Manage systems mainly contained the monitoring of airplane systems and engine parameters. Furthermore, the analysis considered a rough annotation of parallel and sequential task execution. The ANCM domains were regarded as being executed in parallel. This means, that related actions were interleaved, whereas actions of one domain follow a sequential order within the domain.

In comparison to the aforementioned hierarchical high-level task analyses, Wolter and Gore conducted a detailed cognitive task analysis in order to investigate current multi pilot operations (MPO) as baseline for the evaluation of a concept of future SPO [13]. Their concept also considered the support of a single pilot by a remote pilot, so-called ground operator, in nominal operation and in case of contingencies. The regarded flight phases were the approach and landing. A task decomposition spreadsheet was used to list all the actions of the pilot flying, pilot monitoring, automation, ATC and dispatcher. The task analysis covered a nominal and an abnormal scenario, i.e., the approach and landing in Denver and a diversion due to weather conditions. These two scenarios were taken as baseline for the MPO case and for SPO with two different variants of the support by a ground operator. Based on that a workload analysis and comparison of the cases was done. Boy also used a cognitive function analysis in order to explore requirements for SPO in commercial operations [14]. Here, in particular the multi crew cooperation (MCC) of the pilot flying and pilot monitoring was treated. The paper discussed a classical evolutionary and a revolutionary approach for the examination of current function allocation in MPO towards future SPO in CAT. Li and colleagues analyzed also the approach and landing operation of a Boeing 777 for the investigation of current MPO. They identified 52 concrete actions in an HTA used to propose and evaluate changes towards future SPO of operation procedures, crew coordination, use of automation, and responsibilities of an airborne pilot and dispatcher [15].

The previously mentioned work included different objectives and methods used in relation to the application of an HTA. So far these references also exemplify the limitation by focusing on selected flight phases or scenarios. In comparison to that, Stanton et al. applied a SOCA-CAT for MPO regarding a whole flight in general [16]. This work comprises an abstraction hierarchy and work domain analysis with five levels. 16 flight phases and 28 functions were identified, connected and annotated in a SOCA-CAT. Four potential models of SPO were compared to current MPO. A follow-up work evaluated a reduced flight deck crew concept using a Cognitive Work Analysis (CWA) in combination with Social Network Analysis (SNA) [17].

Task analyses were also performed concerning rotary wing aircraft. Jennings et al. conducted a task analysis and workload modelling regarding personnel and autonomy capabilities [18]. They examined the influence of autonomous systems on pilot workload during a conceptual arctic resupply helicopter mission. The workload was compared in two configurations, firstly in a dual pilot operation, and secondly in a single pilot operation supervised by an autonomous agent (AA). The AA was assumed to be a capability embedded in the aircraft avionics hardware and software.

So far, there is no approach for an HTA comparable to the introduced approach that considers a whole flight, operational contexts and concrete functions for normal, abnormal and emergency operations.

III. Previous Work

Before carrying out this HTA, DLR investigated the needs and feasibility of single pilot operation with large airplanes in the institutionally funded research project "Next Generation Intelligent Cockpit" (NICo) [19]. The project intended to develop of a concept and functions for future highly automated cockpits. The goal was accompanied by the development and evaluation of new ways to support single pilots, i.e., by a Virtual or a Remote Co-pilot (VCP/RCP). The VCP comprises enhanced intelligent assistance and robust automation. The RCP represents a qualified and educated ground-based remote pilot. At the beginning of the project commercial multi pilot crews and commercial pilots experienced with single pilot operations were interviewed as subject matter experts (SME) concerning the challenges when operating large and high-performance airplanes. Different aspects and situations were identified and transferred into an event catalog. Related to single pilot operations with large aircraft, problematic situations, i.e., abnormal and emergency situations, were just named as one of the drivers for pilot's concerns. Surprisingly, many concerns referred to normal operation, like handling weather, traffic, specific airport issues or passengers. As a result, one focus for investigations is taken on normal operations [20]. However, apart from the valuable input of the SME, the created event catalog provides just a high-level collection of individual situations and aspects of daily all-weather commercial air transport operations, that are far away from concrete description of procedures, actions and activities of the pilots in the cockpit [21]. Furthermore, NICo figured out what multi crew cooperation and task sharing between the PF and PM means. In this regard, the Quick Reference Handbook (QRH) of an Airbus A320 was examined [21]. The 22 normal standard operating procedures of the QRH were analyzed concerning the task assignment of the pilot flying and pilot monitoring. Of the 907 actions, 463 were assigned to the PF and 444 to the PM.

IV. Approach

The conducted HTA is based on the airplane flight manual (AFM) of the Dassault Falcon 2000EX. The AFM provides a comprehensive, structured semi-formal description of the tasks needed for the operation of the airplane [22]. The AFM contains all procedures used for the operation of the aircraft in normal, abnormal and emergency situations. It represents the reference used for the type certification. In comparison to the QRH and the Flight Crew Operations Manual (FCOM), the AFM specifies the minimum of PF and PM task sharing. The reason why using the AFM as base is, that it provides a specification of the required actions and activities for the operation of the airplane. The PF and PM task sharing and MCC contained in a QRH and FCOM represent company specific extensions of the AFM for a certain airplane. The FCOM is focusing on the specific avionic components, equipment and systems of an airplane. The desired task analysis instead intended to focus on the pure abstract actions and activities used for operating the airplane. Special implementation characteristics of airplane systems are not in the focus, as well as investigating the differences of human machine interfaces (HMI) of different avionic suppliers (e.g., Honeywell or Collins Aerospace). Additionally, there is no standard for the MCC or company related extensions. This means, the FCOM of one company is not equal to the FCOM of the other company for the same airplane and equipment. For the beginning, the MCC plays a subsequent role for the intended HTA. The MCC as a crucial aspect of operational safety and redundancy has to be considered additionally on top of primarily focused flexible task allocation.

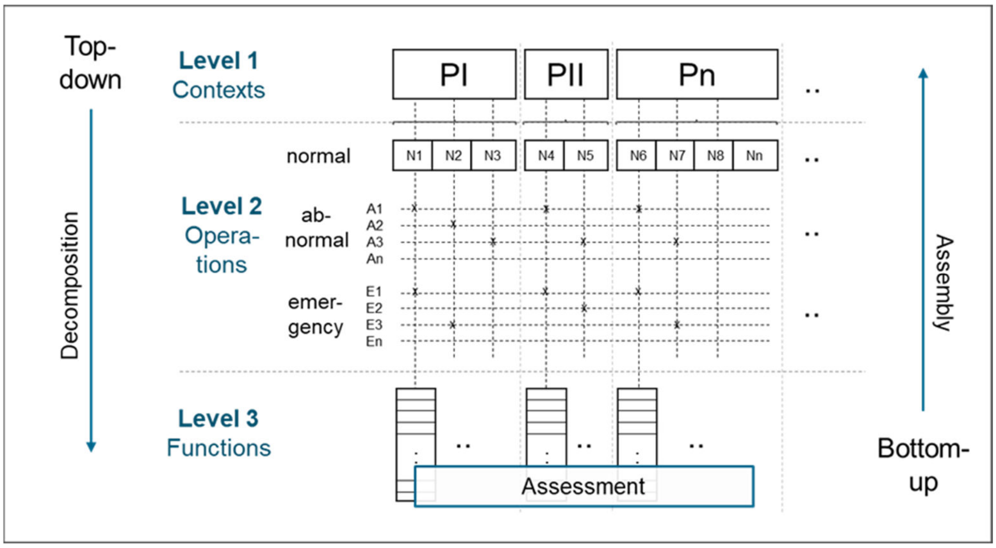

Fig. 1. Coherent linking of the operational context (flight phases) with operating procedures (Standard Operating Procedures) and atomic functions (procedure items and actions) for a systemic and structured decomposition plus bottom-up assembly in a holistic consideration of a flight. Legend: flight phase (P), normal (N), abnormal (A), emergency (E)

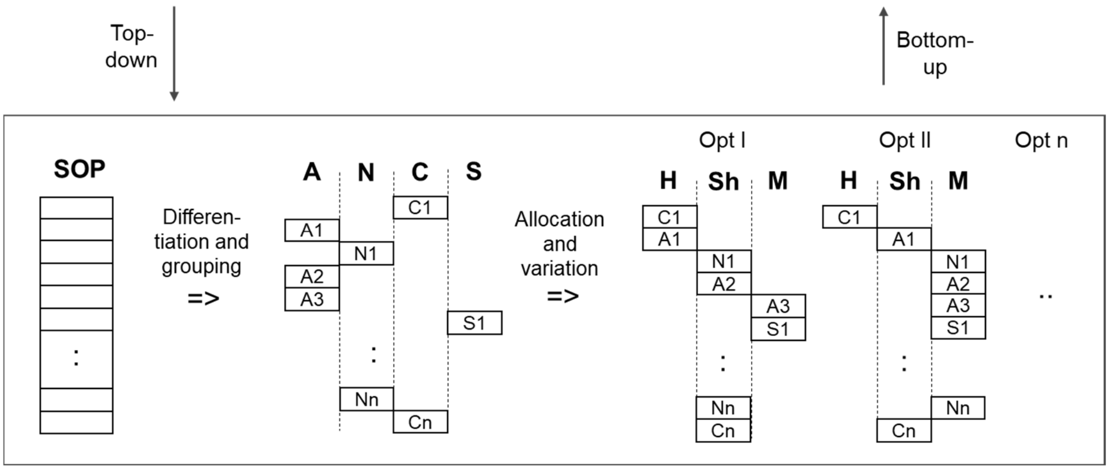

Fig. 2. Differentiation, grouping, allocation and variation of the atomic functions representing the highest level of detail (Level 3). Legend: Standard Operating Procedure (SOP), aviate (A), navigate (N), communicate (C), manage systems (S), option (Opt), human (H), shared (Sh), machine (M)

The approach comprises two parts – a top-down decomposition and a bottom-up assembly of atomic functions for the development of more complex AAS. The assembly of atomic functions includes the evaluation of the automation capabilities of the atomic functions. Fig. 1 depicts the whole approach. Fig. 2 highlights the analysis and differentiation of the atomic functions enabling the development and investigation of a flexible task allocation.

A. Top-down decomposition and task analysis

The first part of the approach, the HTA, starts with the enumeration and consideration of flight phases (*Level 1*). This is followed by the linking of the normal, abnormal and emergency operations specified by the AFM (*Level 2*) with the operational flight contexts. The vertical lines in Fig. 1 depict the connections of a procedure with the operational contexts and flight phases.

All procedures contained in the AFM refer to one or more airplane related phases of flight. This means, that the phases of flight mainly focus on airplane operations, like climbing, acceleration or deceleration, and do not provide a sufficient view and consideration of the operational context of air traffic control. For instance, after taking off, the pilots follow a certain departure procedure. From the AFM's point of view, a departure is reduced to the *After Take-Off* and *Climb* standard operating procedure. For the operation of the airplane, it does not matter that the pilots have to follow a specific departure route with certain lateral, vertical and speed constraints. Hence, the HTA used other flight phases, more oriented to the operational contexts of a flight, i.e., from flight planning till post flight. Due to the fact, that there is no common definition or standard for such operational flight phases and contexts, the analysis is based on an adaptation of contexts mostly used for the subdivision of a flight (see TABLE I). In the following, the airborne flight phases V to X represent the most relevant contexts of operation.

Accordingly, the specific operational context is provided for each procedure. The flight phases can be annotated with further attributes or characteristics, like, if an airplane is operated on ground or in the air or, if a procedure is performed on the apron, parking area, taxiway, runway. Further attributes are, if a procedure takes place in a terminal area in the vicinity of an airport or en-route, in the lower or higher airspace, or over a special country. These distinguishing aspects and context annotations can be extended if necessary.

TABLE I. CONSIDERED FLIGHT PHASES REPRESENTING THE OPERATIONAL CONTEXT INCLUDING ADDITIONAL CONTEXTUAL ATTRIBUTES (*LEVEL 1*)

#	*Flight Phase*	*A/C related*	*On ground*	*Airborne*	*Environment*
I	Flight planning	-	x	-	Office
II	Pre-flight	x	x	-	Apron/Parking
III	Start-up	x	x	-	Apron/Parking
IV	Taxi-out	x	x	-	Taxiway
V	Take-off	x	x	**X**	Runway
VI	Departure	x	-	**X**	Terminal area
VII	En-route	x	-	**X**	ATS-Routes, -Sectors, Countries
VIII	Arrival	x	-	**X**	Terminal Area
IX	Approach	x	-	**X**	Terminal Area
X	Landing	x	x	**X**	Runway
XI	Taxi-in	x	x	-	Taxiway
XII	Shutdown/Parking	x	x	-	Apron/Parking
XIII	Post-flight	-	x	-	Office

The linking and transition from the procedure level (*Level 2*) to the single action items and functions (*Level 3*) is given by the procedure specification within the AFM. Thus, the first part of the approach comprises a holistic view of a flight as well as a coherent top-down decomposition by three levels of detail. This allows the differentiation of atomic functions and use creating larger automation units as well as describing variants for different task allocations. The Autoland system Autonomí developed by GARMIN for single-piloted high-performance airplanes represents an example for more complex and a higher level of automation – not a flexible task sharing [23]. In case of an incapacitation of a single pilot, passengers can activate the Autoland system, which then diverts and re-routes to the nearest suitable airport. The system manages the emergency call to air traffic control (ATC) plus the automated approach and landing, including configuration changes and lowering the gear, till full stop on the runway. In comparison to that, large airplanes can only follow the path of a CAT III instrument landing system and perform the flare and landing in weather conditions no pilot would be able to land safely. However, the gear, speed brakes and configuration have to be operated by the pilots. The GARMIN Autonomí covers all the three levels. Higher levels comprise more complex tasks based on lower-level tasks. This exemplifies, that if lower-level tasks, especially atomic functions, cannot be automated, then a complex AAS would not be achievable. Hence, the top-down decomposition and bottom-up assembly are essential for the development of AAS and a flexible task allocation, and represent a special feature of this hierarchical approach.

B. Bottom-up assessment and assembly

In comparison to the first part and vertical linking using the three levels, the second part focuses on the analysis and linking of the atomic functions, i.e., the connection of the functions regarding Level 3. This part comprises two steps, first the differentiation and grouping of the atomic functions, plus secondly, the investigation of the possible and reasonable application of an atomic function for a flexible task allocation. The principal question is whether an atomic function might be an option for automation or not. This influences the possibility to achieve a flexible task allocation, i.e., providing the option that a pilot or an AAS can execute a task. Whether tasks or functions can be automated or executed by an AAS strongly depends on two prerequisites. The first major requirement is that all needed information for the execution of a task is ascertainable and processable for automation. This means information inside or related to the aircraft as well as outside the aircraft must be accessible for the AAS, e.g., in case of a take-off birds on a runway or the runway and weather conditions. The second crucial requirement is that an AAS needs access to the controls, avionic components or airplane systems, e.g., the autopilot, flaps, speed brakes, gear, flight management system, radio and navigation equipment and so on, in order to perform a certain task and related actions. Furthermore, if tasks should be cooperatively achieved by the pilot and an assistance system, then the controls and input devices must be accessible for both parties properly and transparently.

The analysis and differentiation of the atomic functions is based on the four domains aviate, navigate, communicate and manage systems, here abbreviated by ANCS. Each function is assigned to one of these domains. This differentiation describes a functional and technical context. The first evaluation regarding the automation of the four domains is made by an assessment of the atomic functions in a human centered manner. This means, if it would be conceivable and feasible to automate an atomic function, or should a pilot remain in charge as responsible, e.g., for the verification or validation when applying serious measures. Serious decision subjects are for instance, conducting a diversion, changing relevant values when deviating from the original plan or nominal flight operation, or contingencies.

Finally, the HTA including the three levels of detail and the related linking generate the base for a flexible task allocation, taking atomic functions to build up more complex AAS. Furthermore, the task allocation related to atomic functions or more complex AAS can consider different options for the task assignment. So, the level of automation can be changed by variating the task allocation or the mode for the execution of a function, performed by human, by automation or shared. For instance, the communication with ATC can be performed via voice by the pilot or digitally by automation for standard messages, like position reports or the reception of clearances. The aviate function already provide basic automation capabilities like the manual, selected or managed mode of the autopilot in combination with flight management system. Concerning further automation capabilities, like having an autoland system like Garmin's Autonomí in large airplanes, it is a matter of system design and architecture, granting an AAS access to the gear, slats/flaps and speed brakes. The challenge for future automation applications is to expand the usability of AAS for abnormals and contingencies, e.g., in case of failures or adverse conditions. Here, a flexible task allocation might be an option for future solutions in the way that all basic functions could be handled by the automation as far as possible and in a robust manner whereby the crucial, decisive aspects might be managed by the pilot with support by enhanced assistance systems.

TABLE II. LINKING OF NORMAL STANDARD OPERATING PROCEDURES WITH FLIGHT PHASES (LEVEL 2)

#	***Flight Phase***	#	***SOP***
I	Flight planning	-	-
II	Pre-flight	1	Exterior inspection
		2	Interior inspection
III	Start-up	3	Cockpit check (Electrical power off/on)
		4	Before start
		5	Starting engines
		6	Starting problems
		7	After start
IV	Taxi-out	8	Taxiing
		9	Line up
V	Take-off	10	Take-off
		11	After take-off
VI	Departure	12	Climb
VII	En-route	13	Cruise
VIII	Arrival	14	Descent
IX	Approach	15	Approach
		16	Before landing
		17	Go-around (two engines)
X	Landing	18	Landing
		19	After landing
XI	Taxi-in	-	-
XII	Shutdown/Parking	20	At the ramp
XIII	Post-flight	-	-

V. RESULTS

The following results exemplify the results of the performed HTA. These results represent an extract of the conducted task analysis. More detailed information and results are included in the project deliverable D2.10 [24].

A. *Level 1: Operational context – flight phases*

TABLE I contains all flight phases dividing a whole flight and providing specific operational contexts. The flight phases and contexts form the top level of the hierarchy. Phases related to preceding and subsequent tasks of a flight are also listed, due to the fact that information provided by the flight planning and preparation form the base and default for the following phases and related operations. Nevertheless, the airborne related phases build the main focus of the performed task analysis and flexible task allocation. As shown in the table, the last four columns contain additional attributes and properties for each flight phase, characterizing a context. These support the differentiation and identification of a phase by an AAS.

B. *Level 2: Operations – A/C specific Standard Operating Procedures*

The structured semi-formal task description of normal, abnormal and emergency operations of the AFM are called Standard Operating Procedures (SOP). The included specification of actions, activities, processes and limitations have to be considered by pilots for a safe operation of an airplane and when mitigating contingencies. The analysis regards all SOP, i.e., 20 normal, 77 abnormal plus 21 emergency procedures. TABLE II lists all normal SOPs. The relationship between the flight phases and the SOPs is 1: n, meaning, that a flight phase can be assigned to multiple procedures, but a procedure is linked to one phase only. Additionally, normal SOPs show a deterministic sequential order. The table shows that the Taxi-in operation (XI) is not covered by the airplane flight manual. This means, that there is no dedicated related procedure in the AFM. From the airplane operational point of view, there are no required tasks to be performed in this context, but the related taxi operation from the runway to the parking place is mandatory and has to performed by the pilots, i.e., moving on the taxiways according to the received clearance to a gate or parking position. Climb and descent operations in the en-route phase are also not explicitly covered by a SOP. Hence, the task analysis also identifies needed operations beside the SOPs, for a full functional coverage of the operational flight phases.

TABLE III and TABLE IV provide a figure of the relationship and linking between the flight phases and other normal operations, not covered by the SOPs, plus abnormal and emergency SOPs. Here, a phase can be linked with different procedures, and a procedure can be linked to multiple phases, describing an n:m relationship. The other normal operations fit to several phases. For instance, the ATC interaction and related tasks are independent of the operational context, just the contents and information vary – the procedure of retrieving a clearance or obtaining an ATIS or transmitting a position report are equal for different flight phases. In comparison to that, the abnormal and emergency procedures vary between the phases. There is a difference whether engine problems occur on ground, during take-off or in the air – the same for fire and smoke. Hence, certain SOPs are specified for different flight phases. For simplicity, here the variants of the phase specific SOPs have been combined in one line in TABLE IV, i.e., 77 abnormal SOP are merged to 22 and 21 emergency procedures to 9 lines. The linking of the procedures with the flight phases was done in cooperation with a flight captain owning a type rating for the Dassault Falcon 2000EX and Airbus A320 among others, with several thousand hours flight experience in total.

According to Drury's differentiation of tasks [7], the flight phases and normal operating procedures represents sequential operations while the abnormal and emergency operations are branching operations. Branching means, that the contingency operations deviate from the normal operation path. After the execution of a contingency procedure, when an issue is solved, operation can return to normal operation with or without restrictions. Branching means, taking a diverted path with a sequential order of the SOPs. Parallelism, also called as process control operations by Drury, concern the execution of atomic functions only, not the SOP or flight phases.

TABLE III. LINKING OF OTHER NORMAL OPERATIONS WITH FLIGHT PHASES (*LEVEL 2*)

#	*Flight Phase* / *Operation*	*I Flight Planning*	*II Pre-flight*	*III Start-up*	*IV Taxi-out*	*V Take-off*	*VI Departure*	*VII En-route*	*VIII Arrival*	*IX Approach*	*X Landing*	*XI Taxi-in*	*XII Shutdown / Parking*	*XIII Post-flight*
Xi	**ATC interaction**													
1	Comm. management	-		x	x	x	x	x	x	x	x	x		-
2	ATIS retrieval	-		x					x					-
3/4	Clearance or Instruction reception / Requests	-		x	x	x	x	x	x	x	x	x		-
5	Position reports	-		x	x	x	x	x	x	x	x	x		-
6	Sector / border crossings	-						x						-
Xii	**Repeated operations**													
1	Time & Fuel management	-	x	x	x	x	x	x	x	x	x	x	x	-
2	Weather observation	-		x	x	x	x	x	x	x	x	x		-
3	Traffic observation	-			x	x	x	x	x	x	x	x		-
4	Terrain observation	-				x	x			x	x			-
5	Obstacle observation	-			x	x					x	x		-

TABLE IV. LINKING OF ABNORMAL AND EMERGENCY STANDARD OPERATING PROCEDURES WITH FLIGHT PHASES (*LEVEL 2*)

#	Operation \ Flight Phase	***I Flight Planning***	***II Pre-flight***	***III Start-up***	***IV Taxi-out***	***V Take-off***	***VI Departure***	***VII En-route***	***VIII Arrival***	***IX Approach***	***X Landing***	***XI Taxi-in***	***XII Shutdown / Parking***	***XIII Post-flight***
AB	**Abnormal**													
1/2/3	Engine problems / Thrust Reverser / Levers	-		x	x	x	x	x	x	x	x	x		-
4	Hydraulic System	-				x	x	x	x	x	x	x		-
5	Flight Controls	-		x	x	x	x	x	x	x	x	x		-
6	Landing Gear	-			x	x	x			x	x	x		-
7	Fuel	-				x	x	x	x	x	x			-
8	Electrical	-		x	x	x	x	x	x	x	x	x		-
..	..													
22	Flight Management System	-		x	x	x	x	x	x	x	x	x		-
EM	**Emergency**													
1	Fire and smoke	-		x	x	x	x	x	x	x	x	x		-
2/3	Emergency descent / Rapid depressurization	-					x	x	x					-
4	Windshear recovery	-								x	x			-
5	TCAS II operation	-				x	x	x	x	x	x			-
6	EGPWS operation	-				x	x			x	x			-
7	Systems (hydraulic, generator, ASI)	-		x	x	x	x	x	x	x	x			-
8	Two engine out in cruise and holding	-						x	x	x				-
9	Emergency conditions	-		x	x	x	x	x	x	x	x	x		-

C. Level 3: Functions – Procedure items

TABLE V to TABLE VIII depict the lowest level of the HTA comprising the differentiation, grouping and allocation of atomic functions. The *Item* and *Action* columns contain the SOP specification of the AFM. *Item* specifies a subject, e.g., "*Approach and missed approach procedures*", and *Action* "*set*" a related action or activity to be performed by one of the two pilots. The two information can be understood as a task. Due to the fact that the term task is used for different purposes in different granularity – the pair *Item* and *Action* here represents a function, more precisely an atomic function. Examples for single concrete functions and *Item-Action* pairs are "switching the landing light on", "lowering the gear" or "activating the anti-icing system", or processes, like monitoring the lateral position and height according to the localizer and glideslope deviation indicator in case of an ILS approach. Several of such *Item-Action* pairs form a procedure. A function has to be initiated by a pilot and will be executed by himself or by an airplane system component or both together. Both together means for instance, flying the airplane using the *Selected* mode of the autopilot, where the pilot flying manages the heading, altitude and speed inputs, and the autopilot controls the airplane accordingly. Atomic means that the behavioral specification would not be regarded more in detail. The way how information will be exchanged is linked to the used avionic component, respectively to its HMI. Due to the fact that the items and its actions belong to a certain avionic component – the inputs, outputs and interaction processes are based on a formal and certain interface specification, referring to that particular airplane system or component. Thus, for the beginning of the development of AAS and a flexible task allocation, the way of the input or output of information via a specific HMI is abstractly treated. The granularity of the items and actions in the given procedure description within the AFM is sufficient and fits to the purpose for a basic abstract functional analysis. The items and their actions are concrete enough and can be parameterized according to a related system component. Additionally, the abstract manner of the atomic functions bears the advantage of being open and independent from any details of a specific HMI concept or implementation. Apart from that, it is foreseeable that in the sense of a flexible task allocation between a pilot and automation, the human machine interface and interaction will have to be adapted, compared to the present HMI design. Accordingly, the concrete HMI related questions of dedicated future advanced AAS are subsequent and follow-up work to the HTA and the investigation of principles for a flexible task allocation.

The four SOPs contained in the following tables show a variety of different atomic functions, actions and activities. An action represents a discrete measure. An activity can somehow be more complex, e.g., comprising several actions or repeated actions. Every procedure starts with the name of the procedure as title of the list of action items (item 0). The first action item in the descent procedure (TABLE V), called "*Approach and missed approach procedures – set*", illustrates an activity. The functions behind contain the reading and extraction of information of the cleared approach procedure plus the trans-

TABLE V. FUNCTIONAL DIFFERENTIATION AND GROUPING USING THE EXAMPLE OF THE DESCENT PROCEDURE OF THE DASSAULT FALCON 2000 (*LEVEL 3*)

#	*Item*	*Action*	*Grouping / Allocation*		
			LoD	***ANCS***	***Actor***
0	**Descent**		**2**	**-**	**P/A**
-	FMW window:	-	-	-	-
1	- Approach and missed approach procedures	Set	**2***	**-**	**P/A**
2	- Landing minimums	Set	**3**	**A**	**P/A**
3	- Landing speed	Displayed on ADI - CKD	**3**	**A**	**P/A**
-	ECS synoptic: landing parameters:	-	-	-	-
4	- Pressurization mode	Set	**3**	**S**	**P/A**
5	- LDG elev	Set - CKD	**3**	**N**	**P/A**
6	- Cabin rate	As required	**3**	**S**	**P/A**
7	ANTI-ICE engines, wings and brake (if installed)	As required	**3**	**S**	**P/A**
-	CAUTION When the brake heating system is used (if installed): The minimum required N1 speed with one or both engines operating MUST BE INCREASED by 2%.	-	-	-	-
8	INTERIOR LIGHTS: FASTEN BELTS and NO SMOKING pushbuttons	Pushed set ON	**3**	**S**	**P/A**
9	- Status lights (all 2)	Blue ON	**3**	**S**	**P/A**
10	EXTERIOR LIGHTS: LANDING lights switches (See operational regulations)	ON – PULSE	**3**	**S**	**P/A**
11	- Status light	Blue LDG	**3**	**S**	**P/A**

fer and input of the data into the FMS, navigation and radio communication system. These systems can be separated, represented by single avionic components, but might also be integrated parts of one avionic system, e.g., an electronic flight information system. Due to the complexity of this activity, and that it includes further actions concerning aviating, navigation and communication, the activity is assigned to *Level 2**. The star indicates a small functional procedure – less complex than a SOP but more than one single action which can be assigned to one of the four functional ANCS domains. The other action items of the descent procedure demonstrate typical actions and atomic functions. The differentiation of the actions by the four domains, provides a possible functional grouping of actions. The differentiation and grouping are followed by a first assessment whether an atomic function might be assigned to a pilot and or an AAS. A *P/A* in the *Actor* column indicates that an action could by allocated to a pilot and or an AAS. Again, this assessment depends on the availability of needed informa-

TABLE VI. FUNCTIONAL DIFFERENTIATION AND GROUPING USING THE EXAMPLE OF THE APPROACH PROCEDURE OF THE DASSAULT FALCON 2000 (*LEVEL 3*)

#	*Item*	*Action*	*Grouping / Allocation*		
			LoD	***ANCS***	***Actor***
0	**APPROACH**		**2**	**-**	**P/A**
-	NOTE If approach is performed in icing conditions, report 4-200-05.	-	-	-	-
1	115/230 VAC light pushbutton (option)	OFF	**3**	**S**	**P/A**
2	Altimeters (all 3)	Set - X-CKD	**3**	**A**	**P/A**
3	FUEL SYSTEM: X-BP pushbutton	Close - CKD	**3**	**S**	**P/A**
4	- Status light	Unlighted	**3**	**S**	**P/A**
5	AIRBRAKE: AUTO EXT. pushbutton	On - CKD	**3**	**A**	**P/A**
6	- Status light	Unlighted	**3**	**S**	**P/A**
7	ANTI-ICE: BRAKE pushbutton (if installed)	Off - CKD	**3**	**S**	**P/A**
8	- Status light	Unlighted	**3**	**S**	**P/A**
9	Approach mode	As required	**3**	**A**	**P/A**
10	Pilot flying PDU: ENG TRM BRK window	Displayed	**3**	**A**	**P/A**

tion and data, plus the accessibility of controls and interfaces for the data transfer between automation applications and airplane's systems. Based on the *P*, *P/A* and *A* categorization, further investigation follow, towards concrete automation applications, different options for certain allocation variants forming new ways of advanced human machine cooperation (HMC).

The *descent* and *approach* procedure (TABLE V and TABLE VI) prepare for a landing operation. Hence, both include more airplane system related actions. Instead, the action items of the *before landing* and *landing* procedures predominantly belong to aviate related functions (see TABLE VII and TABLE VIII). Action items 3 and 4 of the *before landing* procedure are assigned to *A*, i.e., automation (TABLE VII). If a shared situational awareness can be achieved by a proper HMI then these two functions could be automated like checklist items that increasingly are automated. TABLE VIII contains the action items of the *landing* procedure. Here, action item 4 represents a special function. This function forms an activity. This activity belongs to the aviate functions and comprises a process in comparison to the other narrowed short-term actions.

VI. DISCUSSION

It must be emphasized, that the approach does not intent to improve the use of automation or current human machine interaction or interfaces. In fact, it intends to enable the investigation of new ways for future task sharing and human machine cooperation. As mentioned previously, the modes of the auto flight system, i.e., manual, selected and managed, represent a very simple form of a flexible task allocation.

TABLE VII. FUNCTIONAL DIFFERENTIATION AND GROUPING USING THE EXAMPLE OF THE BEFORE LANDING PROCEDURE (*LEVEL 3*)

#	*Item*	*Action*	*Grouping / Allocation* LoD	ANCS	Actor
0	**BEFORE LANDING**		**2**	**-**	**P/A**
-	CAUTION To minimize possible flaps asymmetry during approach, extend the flaps one notch at a time.	-	-	-	-
1	Slat-flap handle	SF 1	**3**	**A**	**P/A**
2	Landing gear	Down - CKD	**3**	**A**	**P/A**
3	On HSI: GEAR symbols (all 3)	Green CKD	**3**	**A**	**A**
4	HYD synoptic: hydraulic pressure	CKD	**3**	**S**	**A**
5	Slat-flap handle	SF 2	**3**	**A**	**P/A**
6	Slat-flap handle	SF 3	**3**	**A**	**P/A**
-	AT NOT LESS THAN AUTOPILOT MUH:	-	-	-	-
7	Autopilot	Disengaged	**3**	**A**	**P/A**
-	AT NOT LESS THAN 50 FT:	-	-	-	-
8	Autothrottle	Disengaged	**3**	**A**	**P/A**
9	Approach speed (zero wind, airbrakes 0)	V_REF	**3**	**A**	**P/A**

It exemplifies, how a single task, i.e., flying the airplane, might be assigned to a pilot (*manual*) or to automation (*managed*) or to both (*selected*). Using the results of the conducted analysis for the development of future AAS, a flexible task sharing and allocation as well as HMC, raises a lot of follow-up questions and research topic, like, what rules should be applied to achieve a proper task allocation or what rules provide a guidance to assign an action to Pilot, automation or both? Concerning the latter one, the basic design rule was, that next generation high-performance or large airplanes might offer the option, allowing atomic functions to be performed by a pilot, by automation or both. Thus, the action items of the before landing and landing procedure for instance, might completely be performed by an assistance system, partially in cooperation with a pilot or completely by a pilot. This not fixed function assignment offers a flexibility and provides a redundancy, when an atomic function can be performed by a pilot or automation. This also enable the option of the implementation of a workload reduction and balancing, depending on the prevailing situation, i.e., normal, abnormal or emergency. The differentiation of the atomic functions can be used to combine and group functions of the same domain as well as interconnecting different functional domains for the creation of more complex functions for future AAS. The other question concerning rules for a proper task allocation firstly depends on the target platform, e.g., an existing or future airplane, and the provided automation capabilities regarding the atomic functions. Secondly, the task allocation has to follow a coactive design as described by Johnson and colleagues [25].

TABLE VIII. FUNCTIONAL DIFFERENTIATION AND GROUPING USING THE EXAMPLE OF THE LANDING PROCEDURE (*LEVEL 3*)

#	*Item*	*Action*	*Grouping / Allocation* LoD	ANCS	Actor
0	**LANDING**		**2**	**-**	**P/A**
-	*At touch down*	-	**3**	**N**	**P/A**
1	Airbrakes extension	CKD	**3**	**A**	**P/A**
2	Brakes	As necessary	**3**	**A**	**P/A**
3	Thrust reversers	As required	**3**	**A**	**P/A**
4	Nose wheel firmly maintained on ground.	-	**3**	**A**	**P/A**
5	Steering wheel	Depressed	**3**	**A**	**P/A**
6	Reverser levers	Reversers idle	**3**	**A**	**P/A**
7	Amber TRANS annunciations	On then out - CKD	**3**	**A**	**P/A**
8	Green DEPLOY annunciations	On ACARS-CKD	**3**	**C**	**P/A**
9	Reverser levers	As required	**3**	**A**	**P/A**
-	*At 30 KIAS:*	-	-	-	-
10	Reverser levers	Reversers idle	**3**	**A**	**P/A**

A coactive design includes the analysis of suitable variants of proper task allocations regarding normal operation and contingencies as well as an interdependence analysis [26] in order to elaborate who should perform which task. For instance, in demanding, abnormal or emergency situations, the automation should manage the flying activity, if possible. This is exactly what pilots do in demanding or critical situation, if the autopilot could be engaged, they engage the autopilot, saving resources and facing relevant issues. Roth and colleagues reviewed approaches to function allocation regarding human machine teaming and levels of autonomy. They proposed an integrated approach for the design of function allocations [27] which might also be used for the development of a flexible task allocation.

Concerning decision making, it has to be pointed out, that the three levels of the approach also form levels of abstraction regarding goals, priorities and functionalities. The decision making refers to each level. This means, that each level includes its own targets, issues, options and measures being part of a related decision making and mitigation process.

As before, automation and enhanced assistance systems for large and high-performance airplanes will incrementally grow. Accordingly, the development of single AAS intends an incremental implementation and realization of a flexible task allocation.

VII. SUMMARY AND CONCLUSIONS

So far, the mentioned task analyses were either restricted regarding the flight contexts, phases, operations, e.g., use cases or scenarios, or limited concerning the level of detail. The introduced new HTA approach instead provides a systemic and holistic approach - the first approach, that considers a whole flight, operational contexts plus detailed concrete actions concerning normal, abnormal and emergency operations. The deterministic, coherent linking of operational contexts with operating procedures including atomic functions provides semantical context to operations and functions. The linking allows a differentiation concerning three levels of detail as well as a differentiation within each level, i.e., the flight phases (*Level 1*), the normal, abnormal and emergency procedures (*Level 2*) as well as the atomic functions concerning its function domain (ANCS), automation capabilities and task allocation (*Level 3*).

The systemic approach also facilitates the identification of further functions and operations that are needed for the whole flight operation from an air traffic management perspective, i.e., other additional normal operations, i.e., ATM and aircraft related tasks (TABLE III). Furthermore, flight phases have been identified by this approach, where the SOPs do not or just partially cover the needed operations, e.g., the en-route and taxi-in phase. Hence, the presented approach supports a functional and operational completeness and coherence.

The linking enables the examination of a flexible task allocation on top of the automation of atomic functions and operating procedures. A key feature of the approach is, that the atomic functions are concrete and detailed but abstract. This means, that implementation details of specific products and components neither influence nor restrict the analysis and the development of advanced assistance and automation applications. The abstract functional and operational base allows the incremental development of a flexible HMC and new related HMI. Based on the results, fundamental aspects and possible task allocations between pilots and future automation are currently investigated in a simulator study with airline pilots. At present, DARWIN develops and evaluates concrete AAS with respect to which tasks might be feasible, not too complex or expensive for automation. Further details and results of the presented approach can be found in the Deliverable D2.10 Report on Task Analysis and Redistribution for upcoming SPOs [24].

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