Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015)

Computational Assessment of Different Air-Ground Function Allocations

Martijn IJtsma and Prof. Jacco Hoekstra
Faculty of Aerospace Engineering
Delft University of Technology
Delft, the Netherlands
m.ijtsma@student.tudelft.nl, j.m.hoekstra@tudelft.nl

Raunak P. Bhattacharyya and Dr. Amy Pritchett
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA USA
rpb6@gatech.edu, amy.pritchett@ae.gatech.edu

Abstract—**NextGen and SESAR are re-defining each agent's role in the airspace in terms of autonomy, authority and responsibility. Function allocation is the process of defining authority, i.e., which functions are executed by which agents. This is an essential design decision in creating transformative ATM concepts of operation. This paper presents a computational simulation methodology to assess function allocations in early design phases, before functional prototypes and HITL experiments can be developed. Thus, this method applies the same models of the functions regardless of which agent executes them, so that any observed effects can be isolated to the function allocation without confounds. A case study is presented in which ten potential function allocations within a new concept of operation were evaluated. A distinction is made between coherent and incoherent function allocations. The key metrics of the function allocations include the time history of each agent's task load and required information exchange with other agents. The results show that the coherency of a function allocation can have a pronounced effect on the amount of information requirements. The paper concludes with a discussion of how this method can be applied to other concepts of operation, and how this method can be used, after the early-in-design analysis described here, as an evolving computational analysis tool for more detailed evaluations using higher fidelity models.**

Keywords - air-ground function allocation; multi-agent simulation; air traffic management; verification and validation

I. INTRODUCTION

The Next Generation Air Transportation System (NextGen) in the US and the Single European Sky Air Traffic Management (ATM) Research (SESAR) program in Europe are redefining ATM. In the farther term, these programs may re-define roles of the agents in a manner that can be framed as changing the autonomy, authority and responsibility (AA&R) of the agents, and correspondingly their interactions. To be precise, this paper uses the following definitions:

- *Autonomy* is defined here to delineate whether an agent can perform a function independently. In the context of ATM, novel distinctions of agent autonomy are emerging in which a ground controller may be able to fly an aircraft, or in which a pilot may be able to self-space and self-separate in a "free-flight" environment.
- *Authority* is defined here to delineate which functions an agent is asked to perform.
- *Responsibility* is defined here to delineate which outcomes an agent will be accountable for in an organizational, regulatory or legal sense. Authority and responsibility need not always be aligned. For instance, in an air traffic sector, the responsibility for a smooth traffic flow may remain with the air traffic controller even as the aircraft flight crews are given the authority to maintain spacing. This mismatch implies extra work from the air traffic controller in the form of monitoring and, as necessary, intervening.

Function allocation is the process of defining which agent has authority for which functions, and responsibility for the outcomes of these functions. This function allocation may be fixed. However, it can also be dynamic. Key examples of current-day dynamic function allocation include the changes in pilots' authority and responsibility inherent with the triggering of a TCAS Resolution Advisory, and the changes in both pilots' authority and responsibility when they accept a clearance for a visual approach. Future NextGen and SESAR concepts of operations may dramatically increase the number of potential function allocations of authority and responsibility, and triggers for dynamic re-allocation.

At the highest-level of analysis, the functions that must be performed within a concept of operations can be modeled as generally the same regardless of which agent they are allocated to. For example, regardless of whether it is flown by the autopilot, an onboard pilot or a remote controller, the aircraft control surfaces must be regulated towards the same laws of physics. Likewise, the physics underlying trajectory optimization, guidance, spacing and sequencing are generally the same regardless of agent.

Even when the functions are assumed to be performed the same way by different agents, the allocation of authority for these functions can have significant impact on the agents themselves, on requirements for information transfer between agents (by whatever communication mechanisms), and potentially on system performance. For instance, new concepts of operation that allocate in-trail spacing functions to the flight deck may significantly reduce the task load of the air traffic controller (which may or may not be beneficial), while increasing both the task load assigned to aircraft agents (notably, the flight crew) and the requirement for information transfer between the controller and the aircraft about spacing.

Further, these effects may be eased or aggravated by the *coherence* of a function allocation [1]. Many functions naturally go together in terms of the information they act upon and the actions they take. Thus, they can benefit from the same information sources and, when conducted together by the same agent, can be timed and executed synergistically: this would form a coherent function allocation. Conversely, incoherent function allocations could require different agents to interleave their activities, each waiting upon the other, to perform related functions; likewise, such interleaved activities could require substantial information to be transmitted between agents to coordinate their functions. Specific metrics of a function allocation, then, can include the task load of each agent (in the aggregate, but also relative to limits on task load at any period of time), and the amount of information transfer requirements between the agents.

Currently, methods to design new concepts of operation, specifically concepts which are aimed at novel distributions of AA&R, rely heavily on subject matter experts who, in turn, rely on heuristics, experience, or rules of thumb. Testing methods typically rely on Human-In-The-Loop (HITL) simulations which, while being the appropriate final test before implementation, occur too late in the design cycle for easy testing of key issues that may require significant changes to the entire concept of operation or to supporting technologies.

This paper instead proposes that during the early phases of design, before significant commitments have been made in terms of developing prototypes and technology, the relative costs and benefits of varying function allocations can be computationally assessed. These results can then be used to guide the detailed procedure and technology design, and identify potential key human factors issues that might merit research. Thus, instead of investing time, effort and money to develop prototypes only to later realize that the underlying function allocation yields poor performance, this paper proposes a methodology by which the design process can first evaluate multiple possible function allocations.

The proposed method extends beyond past evaluations of function allocations, which have generally focused on specific, isolated functions. For example, an HITL study at Eurocontrol examined controller activity with and without the allocation to the flight deck of merging and in-trail spacing functions [2]. This study found that the allocation of these functions to the flight deck not only reduced the number of communications that the controllers had to initiate to the aircraft – it also changed when these communications were made.

Other examples of studies compared air-ground function allocation of the separation assurance task. For example, two HITL studies at NASA, one controller-focused and one flight deck-focused, compared the effects of mixed-equipage in delegating separation functions to some aircraft [3]. Likewise, under the Advanced Air Transportation Technologies (AATT) program, a study at NASA Ames investigated the performance of Distributed Air Ground Traffic Management (DAG-TM) [4]. Two competing en-route concept elements examined delegating the separation assurance task to the flight deck or leaving it on the ground with trajectory based operations. Initial results showed a benefit of moving some responsibilities to the air in terms of flight efficiency, notably flight time. Similar results were found by NLR in an HITL study, part of the European INTENT project [5]. This project investigated the level of intent information requirements due to a different task allocation but also found differences in terms of airspace capacity. These studies represented substantial research efforts that simultaneously examined both different function allocations and how automation and algorithm design (e.g., the conflict detection look-ahead) might vary with different function allocations.

A computational study of tactical conflict resolution in an en-route free flight environment similarly assessed the impact of varying the ‘locus of control’ in conflict detection and resolution functions from being solely allocated to the ground controller to an increasing proportion of the aircraft (up to 100%) [6]. While the results were specific to conflict detection and resolution in free flight, this study emphasized the benefits of computational modeling as a cost- and time-effective form of analysis, and modeled the functions as being completed the same by all the agents so that any observed effects could be isolated to the function allocation without confounds, an attribute that this paper’s proposed method continues.

This paper first describes the methodology proposed here, which expands upon these studies by creating and applying a flexible simulation framework that is not specific to one phase of flight or concept of operation, but instead can be applied to quickly examine many different types of operation. Next, this methodology is applied to in a case study of terminal operations involving merging and spacing operations within a stream of aircraft performing Optimal Profile Descents (OPD). Finally, this paper concludes with a discussion of the capabilities of this method and further potential extensions.

II. Method: Simulating Multi-Agent Work

Work Models that Compute (WMC) is a simulation framework and engine, implemented as open source software written in C++, which is capable of modeling and simulating multi-agent concepts of operation [7]. A concept of operation is modeled by modeling the functions that must be performed, and the distribution of authority for those functions among the human and automated agents within a team. Thus the functions are represented in work models independent of the agents [8].

In the WMC framework, agent models do not contain any representation of the work; the teamwork and taskwork are instead represented by actions and resources in the work model. A resource represents a tangible aspect of the environment and the collective set of resources represents the entire environment. An action is a distinct work process which is temporally and organizationally atomic in that it can be undertaken at its own time relative to other work activities and is undertaken by one agent at a time. Once the work models are developed, the actions are linked during runtime to agents.

These WMC work models need only represent the functions inherent to the concept of operation, without extensive models specific to particular technologies or applications. Thus, the framework provides a flexible, easily-configured tool for examining a wide-range of concepts. At this time, it has been used for the European terminal operations case study noted in this paper, and has also been used to simulate four hours of operations of a U.S. en-route center [6], and to examine the detailed interactions of human and automated agents during NextGen operations into KLAX.

A. Modeling and Measuring Function Allocation

A function allocation is represented in WMC as distribution of authority to agents to perform each action in a concept of operation's work model. Different function allocations can be tested in different simulations of the same scenario using the same work model. Moreover, dynamic function allocations can be created that dynamically update or adapt the function allocation within a simulation run.

WMC gathers metrics of function allocations that are independent of the allocations themselves. These metrics are assessed during computational simulation but are also applicable to any subsequent high-fidelity HITL simulations. First, WMC records a trace of all the actions along with the exact time when these actions were performed, and the agents who performed them. Second, WMC records a log of all the time instances when an action allocated to an agent needs to "get" the value of a resource that is "set" by an action allocated to a different agent. Thus, this log gives a time trace of all instances of information requirements which predict the exact instances requiring information transfer between agents. The information requirements are also a measure of coherency in that, the more an agent is dependent on the actions of another, the lesser the function allocation's coherence.

III. Case Study: Air-Ground Function Allocation of Terminal Area Merging and Interval Management

This case study analyzes different function allocations in merging and interval management (IM) between air and ground in the terminal airspace of Schiphol Airport, representing mid-term proposed concepts of operation in NextGen and SESAR. Some studies have analyzed the allocation of IM between air and ground, particularly in HITL simulations [9]. In contrast, through its fluid function allocation WMC allows for the quick comparison of a range of conventional and non-conventional function allocations.

A. Scenarios

In two simulated scenarios, IM and merging functions sequence aircraft over the runway threshold with 60 second time intervals. Three aircraft are merged into one stream for RWY 18R, as shown in Figure 1. One aircraft enters from the South-West, following the RIVER arrival route on an OPD profile. The other two aircraft enter from the East and follow the ARTIP arrival route. The first aircraft starts on the profile for an OPD and the second follows at a 60 second time interval. The routes merge at waypoint EH608, and the aircraft on RIVER is designated to be the lead aircraft that can continue along an OPD profile and the other aircraft will need to deviate from the OPD to follow the lead aircraft.

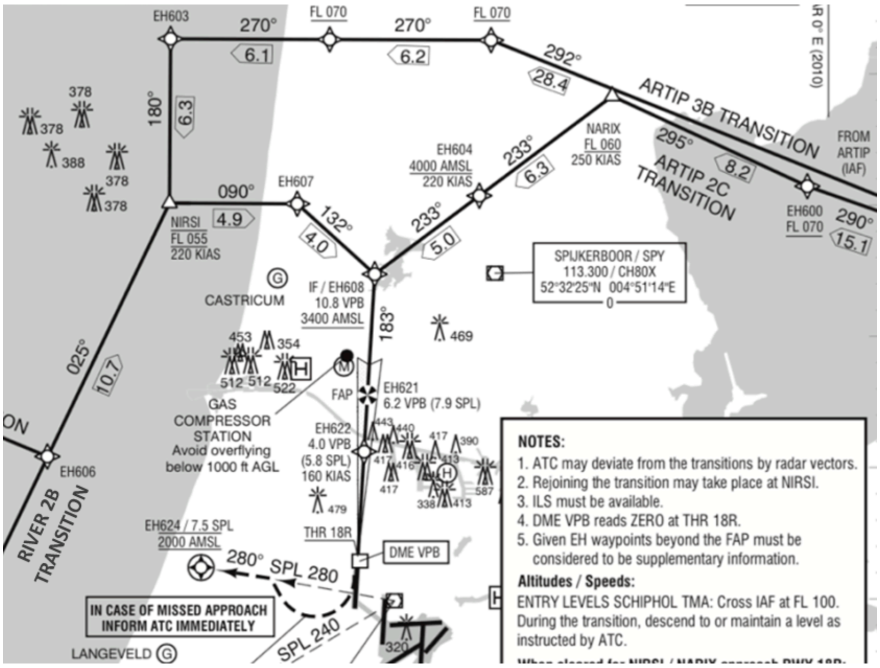

Figure 1: Approach chart for Schiphol Airport RWY 18R (adapted from ATC the Netherlands).

TABLE I. ACTIONS WITH DESCRIPTIONS

Action name	Action description
	Vertical Path Management
Start descend	Determine top of descent (TOD) and initiate 2 degree glide slope descent.
Set flaps and speedbrakes	Set flaps and speedbrakes based on flaps and speedbrakes speed restrictions.
Deploy gear	Deploy gear when below 2,000 ft.
Intercept ILS	Intercept ILS signal and initiate 3 degree glideslope descent.
Land aircraft	Land the aircraft (remove aircraft from simulation).
	Lateral Path Management
Manage waypoint progress	Set the target waypoint.
Direct to waypoint	Set the heading based on the target waypoint.
Calculate distance to waypoint	Calculate the distance to the next waypoint. This action is needed for managing the waypoint progress.
Calculate distance to runway	Calculate the remaining distance to the runway. This action is needed to calculate TOD.
Command path stretching maneuver	Command a path stretching maneuver in response to the aircraft sequencing.
Execute path stretching maneuver	Execute a trombone or fanning maneuver, depending on which arrival stream the aircraft is on.
	Speed and Interval Management
Calculate distance to mergepoint	Calculate the distance to the mergepoint. This action is required to determine the arrival sequence at the mergepoint.
Determine arrival sequence at mergepoint	Determine the arrival sequence at the merge point to determine lead and follow aircraft for IM. Also check whether a path stretching maneuver is required.
Command OPD speed cues	Command an airspeed at a given altitude for OPD.
Assign lead aircraft	Set the lead aircraft for IM.
Calculate IM airspeed	Calculate the required airspeed to maintain the stipulated interval. This is currently done through a PD controller, but any IM algorithm can be used.

Both a nominal scenario and a non-nominal scenario are simulated. In the nominal scenario the aircraft are sequenced according to their respective distances to the runway. In the non-nominal scenario the RIVER aircraft needs to land first, even though it would not be the first in line based on distance from the runway, representing a situation where one aircraft needs to be given priority (e.g., a medevac flight). This then requires vectoring the aircraft arriving on the ARTIP route to delay their arrival time to allow Aircraft 1 to pass in front.

B. Computational Model of Actions and Agents

To represent this case study, a total of 17 actions have been created, as shown in Table I. The focus of the case study is on the allocation of authority. Actions associated with the distribution of responsibility (monitoring, intervening etc.) are not modeled. The aircraft are modeled with a non-linear 6DOF dynamic model, with aerodynamic and mass properties of roughly a B747. The autoflight system is simulated using a model referenced adaptive controller that seeks to establish the closed-loop dynamics of an actual large transport aircraft. It has control loops for most often-used flying modes, such as flight path angle, airspeed and heading.

Four agent models are invoked: three airborne agents (flight crew/flight deck automation), one for each aircraft, and one ground-based agent (an air traffic controller/ground-based automation). All agents are assumed to be perfect agents in that they perform all tasks instantaneously and without error, do not forget actions, have infinite capacity of actions stored in queue and commit no errors in either reading or setting of values. In this way, the results will reflect the task load and information requirements demanded of the agents by the concept of operation and function allocation.

C. Function allocation

Different function allocations are created by varying which agent does each action in any simulated flight. These actions naturally are grouped into functional blocks, as shown in Table II. This case study examined the 10 different function allocations in Table II. The first 9 'coherent' allocations represent the gradual shift of entire functional blocks from ground to air. With allocation FA1, all functional blocks are allocated to the ground-based air traffic control agent. Progressively more blocks are allocated to the aircraft finally culminating in FA9 where all actions are allocated to the flight crew agents.

Function allocation FA10 in the far right column of Table II represents an 'incoherent' function allocation in that related actions are distributed between air and ground, breaking up the functional blocks. This forces the agents to exchange information with other agents as part of most of their allocated actions, and intertwines their activities.

D. Results

Figure 2 shows the lateral paths of the aircraft in the non-nominal scenario. AC1 enter the airspace from the South-West and AC2 and AC3 from the East. Once AC1 is designated as landing first, AC2 and AC3 need to perform fanning maneuvers to delay their arrival time (EH608) by vectoring off the original approach path to intercept the final approach fix about 3 nm further out. In the nominal scenario the aircraft fly from NARIX to EH608 in a straight line.

Figure 3 shows the altitude and speed profiles. All aircraft start at an altitude of 9,000 ft with an initial speed of 240 kts IAS. All aircraft are continuously descending while reducing their speeds in a stepwise manner. Their final approach speed is 150 kts IAS. AC1 and AC2 start the scenario performing an OPD. Depending on the scenario (non-nominal/nominal),

TABLE II. ACTIONS GROUPED INTO FUNCTIONAL BLOCKS AND ASSIGNED WITHIN 10 DIFFERENT FUNCTION ALLOCATIONS

Functional blocks	**Actions**	**Coherent allocation of entire functional blocks**									
		Coherent									**Incoherent**
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Vertical profile management	Calculate distance to runway	G	A	A	A	A	A	A	A	A	G
	Start Descend	G	A	A	A	A	A	A	A	A	A
	Intercept ILS	G	A	A	A	A	A	A	A	A	A
	Land Aircraft	G	A	A	A	A	A	A	A	A	A
Aircraft configuration management	Set flaps and speedbrakes	G	G	A	A	A	A	A	A	A	A
	Deploy gear	G	G	A	A	A	A	A	A	A	A
Lateral control	Direct to waypoint	G	G	G	G	A	A	A	A	A	G
	Calculate distance to waypoint	G	G	G	G	A	A	A	A	A	A
Speed control	Set Airspeed	G	G	G	A	G	A	A	A	A	G
Lateral profile management	Manage waypoint	G	G	G	G	G	G	A	A	A	A
	Execute path stretching maneuver	G	G	G	G	G	G	A	A	A	A
Speed management	Command OPD speed cues	G	G	G	G	G	G	G	A	A	A
	Calculate IM Airspeed	G	G	G	G	G	G	G	A	A	A
Non-nominal situation management	Command path stretching maneuver	G	G	G	G	G	G	G	G	A	G
	Calculate distance to merge point	G	G	G	G	G	G	G	G	A	G
	Determine sequence at merge point	G	G	G	G	G	G	G	G	A	A
	Assign lead aircraft	G	G	G	G	G	G	G	G	A	G

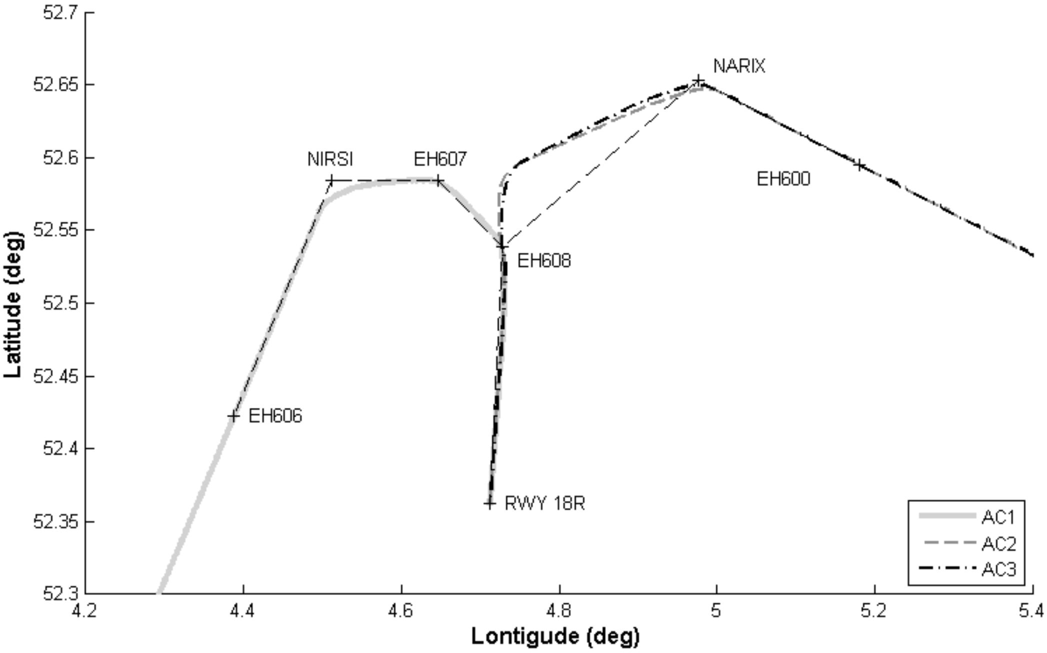

Figure 2: Aircraft lateral paths in the non-nominal scenario. RIVER arrival route enters from the bottom left via EH606 and the ARTIP route enters from the right via EH600.

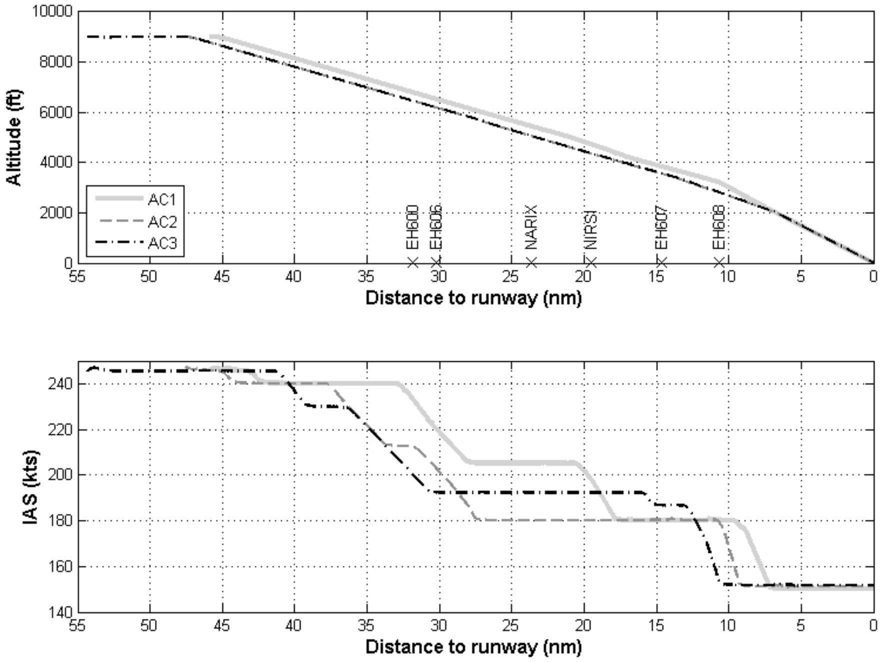

Figure 3: Altitude and speed profiles of the three aircraft in the non-nominal scenario.

either AC1 or AC2 is designated to be the lead aircraft for IM, respectively, at about 38 nm from the runway threshold. The lead aircraft continues the OPD while the trailing aircraft maintain 60 seconds time intervals through IM. Both Figures 2 and 3 serve as verification that the combination of actions produces the desired outcome, i.e., they produce realistic 4D approach trajectories. Figure 4 shows the total task load of each agent with each function allocation, measured as the number of actions from Tables I, II and III executed during each simulation of the scenario, omitting three actions (Calculate IM Airspeed, Calculate Distance to Runway and Calculate Distance to Waypoint) that are monitored frequently but only serve to trigger actions that are recorded here. Beyond the aggregate results shown in this figure, the outputs of the simulation also include the detailed traces of what action each agent needed to perform at what time, which can help inform procedure, automation and training design.

The first nine allocations show a predictable pattern in that the task load of ATC decreases and the task load of the flight crews increases when allocating more functions to the flight deck. For FA1-FA4, the air traffic control agent has a high task load as it is handling three aircraft at the same time; these results would require more detailed examination if these function allocations were proposed, and might warrant controller decision aids or multiple controllers to keep the task load manageable. For FA7-FA9 the air traffic control agent has a lower task load: about ten actions over a time span of 800 seconds. Such low task load could lead to potential problems with low task engagement.

The task load is fairly evenly distributed between the three aircraft agents in all the function allocations. Their task load increases gradually in transitioning from FA1 to FA7. Once reaching FA7-FA9, in which speed and emergency management are allocated to the aircraft, the task load reaches a consistent, high level.

Figure 5 shows the total amount of information transfer requirements for each agent with each function allocation. These results are different than the task load results: the agents' information transfer requirements are substantially higher in the 'middle' function allocations FA4-FA7. This wave pattern is the result of intertwined work being split up and allocated between agents, which happens particularly in allocations where all agents perform about the same amount of taskwork. It demonstrates that information transfer will need to increase when functions are more equally allocated between air and ground. High information transfer requirements will require extra tools and efficient communication channels to allow the agents to perform their work appropriately.

Examining FA10, the function allocation tested here purposefully to demonstrate incoherence: while the task load for each agent seems reasonable, information transfer requirements are very high. In fact, the amount of information transfer required by the ATC agent has tripled with respect to the next-highest amount of information requirements found with the coherent, but evenly allocated between air and ground, FA5 and FA6.

Figure 4 also illustrates how task load distribution and information requirements vary between the nominal and non-nominal scenarios. In the non-nominal scenario, AC1 requires priority in the sequencing onto the final approach path. In FA1 and 2, in which the air traffic control agent is allocated most of the functions, it has higher task load in the non-nominal case. As the functions are transitioned to the aircraft in the higher-number function allocations, the extra task load added by the non-nominal scenario is also transitioned to aircraft – but, perversely, the extra task load is not incurred by the aircraft creating the non-nominal scenario (AC1), but instead onto the aircraft that is following it (AC2). This reflects the extra path stretching maneuver that AC2 now needs to perform. This extra task load does not continue further back in the aircraft sequence as the impact on AC3's task load seems to be limited. Figure 5 shows that the information requirements do not show a consistent difference between the nominal and non-nominal scenario.

Time traces of information requirements further highlight times where more information transfer will be required. For example, Figure 6 shows the time traces for the three aircraft agents with FA4. Although the taskwork of each of the aircraft agents is roughly the same, AC2 and AC3 experience periods requiring frequent information transfer, while AC1 has information transfer requirements that are fairly distributed over time. These frequent information transfer requirements are caused by IM actions: just after 100 seconds the sequencing operations and IM are initialized, which require AC2 and AC3 to slow to maintain their interval behind AC1.

Similarly, Figure 7 shows the information requirements time traces for the air traffic control agent in the nominal and non-nominal scenarios. It can be seen that in both scenarios the air traffic control agent experiences high information transfer requirements that occur in peaks. In the non-nominal scenario the information requirements are more concentrated after around 400 seconds.

This analysis of information transfer requirements can be taken further. The outputs of the simulation also include the detailed traces of which information elements will be needed by which agent and at what times. This can help determine the technologies or procedures by which they are transferred, including broad decisions such as whether the information is 'pushed' or 'pulled', and communicated automatically or by direct communication between human agents.

IV. Discussion and Conclusions

This paper proposes that operational problems inherent to a concept of operation's function allocation can, and should be identified in early design phases, when significant changes can still be made to the design. The methodology that is outlined and demonstrated in this paper is capable of predicting task load and information requirements in a dynamic, multi-agent concept of operation, without the need of HITL experiments or development of prototypes. It thus provides a valuable evaluation tool for the design and analysis of function allocations in new concepts of operation.

A case study analyzed ten possible function allocations between air and ground for terminal operations in a NextGen/SESAR concept of operation. Two scenarios (nominal and non-nominal) were studied with three aircraft performing IM and merging operations. The same actions were performed in each scenario, but their allocation between agents was varied. Nine of the allocations examined a range of coherent function allocations ranging from "everything allocated to the air traffic controller agent" to "everything allocated to the aircraft." The tenth represented an incoherent function allocation.

The simulation provided task load and information transfer requirement traces for each agent. The results showed that when tasks are more evenly allocated between the agents, the task load per agent decreases but the information transfer requirements increase. Further, the simulation output also includes the detailed trace of when each action must be executed by each agent, and which elements of information transfer each agent will require when; this provides a systematic and comprehensive method for designing technologies, procedures and training to perform the actions. Likewise, this provides the basis for deciding on information transfer between agents, including broad decisions such as whether the information is 'pushed' or 'pulled', and whether it is communicated automatically or directly between humans.

Further, the qualitative notion of the "coherency" of a function allocation was found to have a large quantitative impact on the information transfer requirements between the agents. When functions that are naturally grouped together are allocated to the same agent, information transfer requirements are lower. Such coherency can be fostered when making function allocation decisions by cognitive work analysis techniques that identify which functions naturally operate on the same information.

In the current simulation all actions are performed the same way irrespective of the agent who performs them. We propose that this approach provides a useful, indeed necessary, baseline. Most notably, if the concept of operation does not execute as desired with these perfect agents, the source of the poor performance is unambiguously isolated to the function allocation and concept of operation itself.

After this baseline, further simulations using this method and simulation framework can examine a number of further effects as the concept of operation is refined, which may then further impact system performance. These can include:

- More detailed models of the actions that also enable more interacting agents. For example, rather than modeling just an 'aircraft' agent, studies could examine a 'captain', 'first officer', and 'autoflight' agent to examine how air-ground function allocations then translate to the within-aircraft function allocation.
- Examining more detailed models of how the functions might be performed by different agents. For example, different models of how the function might be performed can be implemented and varied depending on the agent that has authority for it.
- Examining more detailed models of how the functions might be performed by the same agent in different contexts. For example, different models of how the function might be performed can be implemented and varied depending on contextual factors including phase of flight, availability of information, and the immediate task load of the agent.

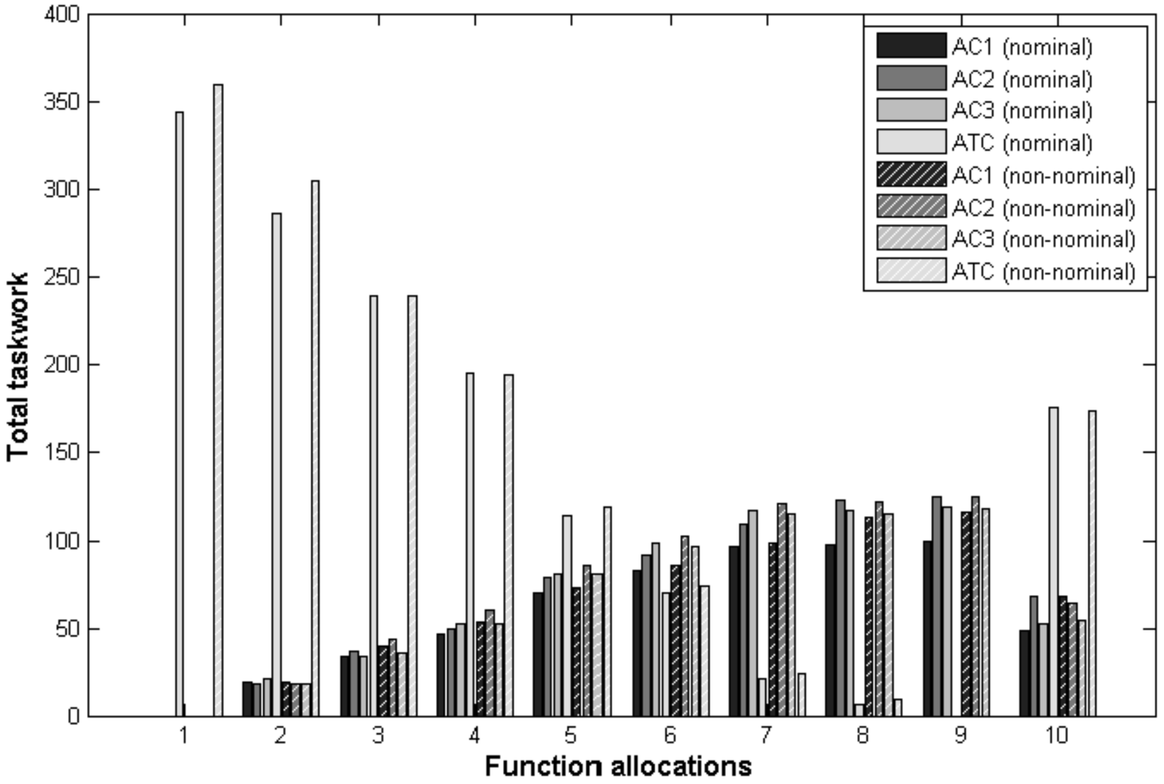

Figure 4: Taskwork for each agent and function allocation in the nominal and non-nominal scenarios.

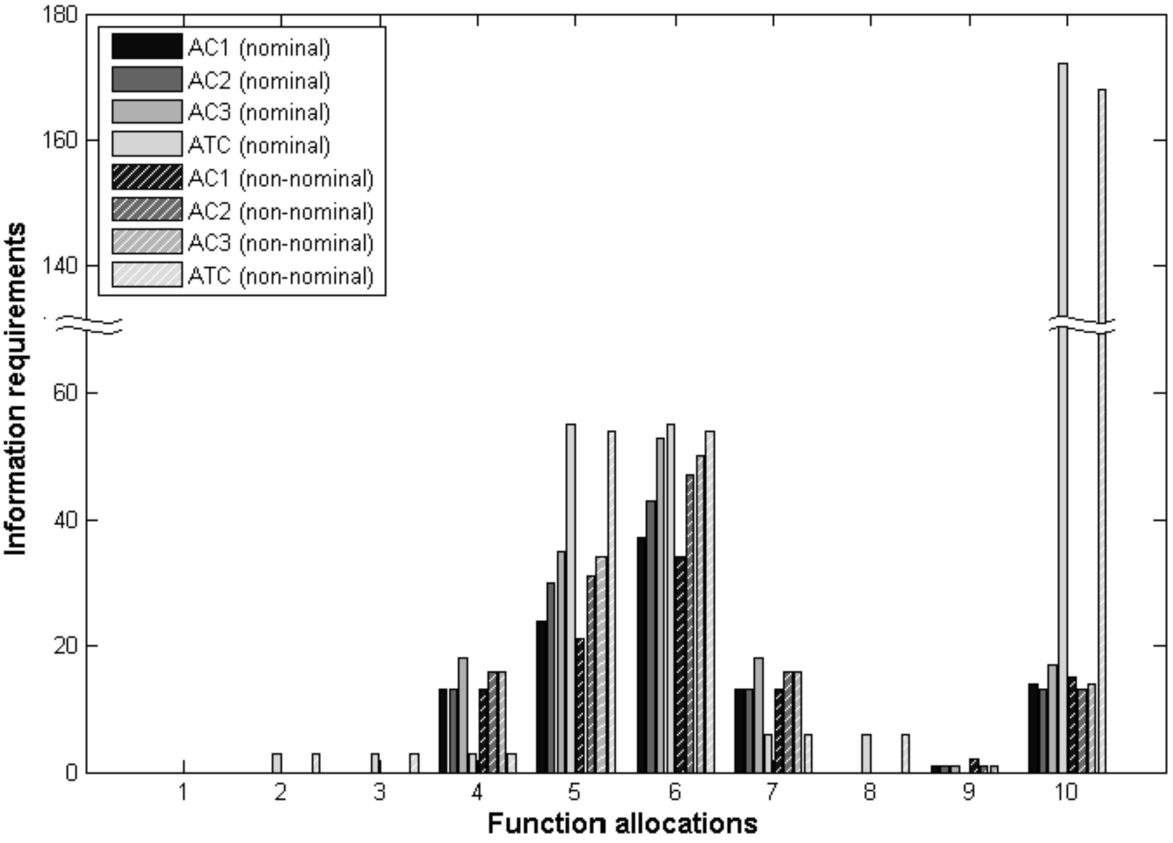

Figure 5: Information requirements for each agent and function allocation in the non-nominal scenario.

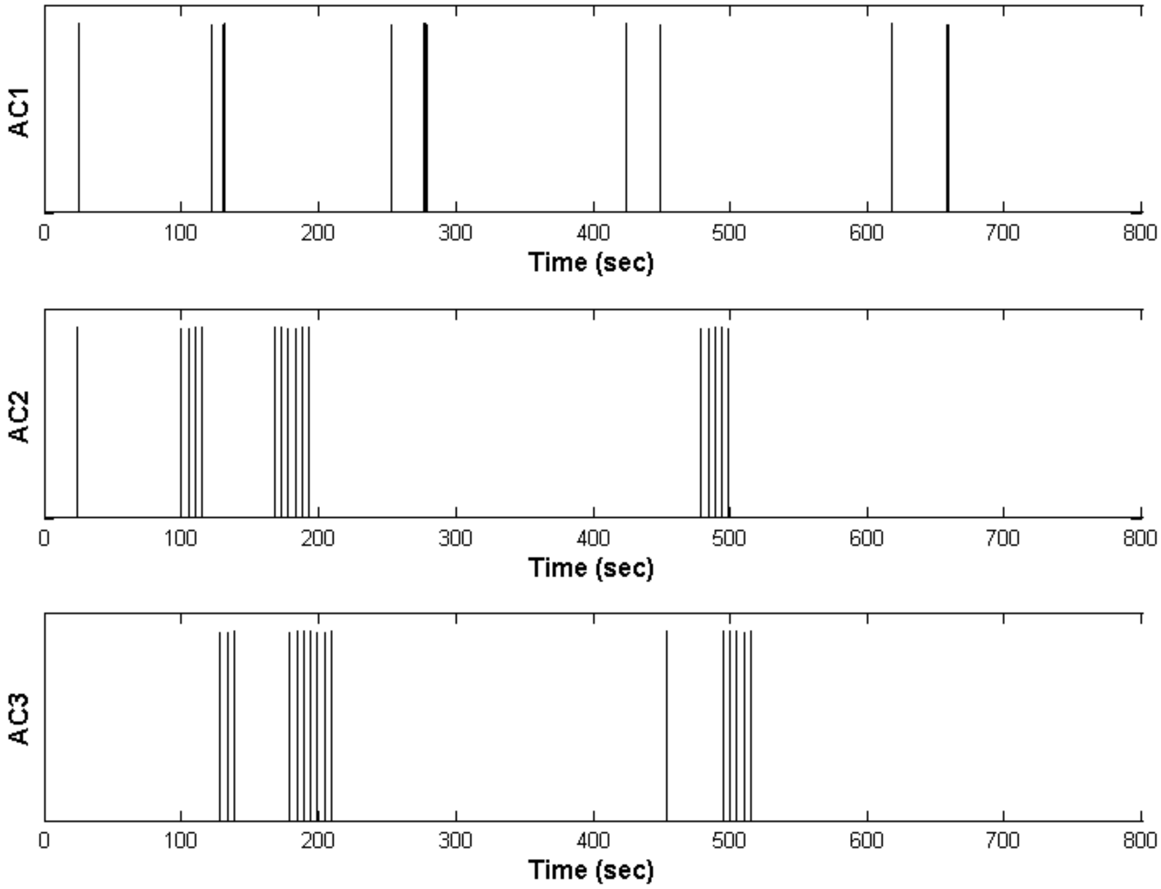

Figure 6: Time traces of information transfer requirements for the aircraft agents with FA4, in non-nominal scenario.

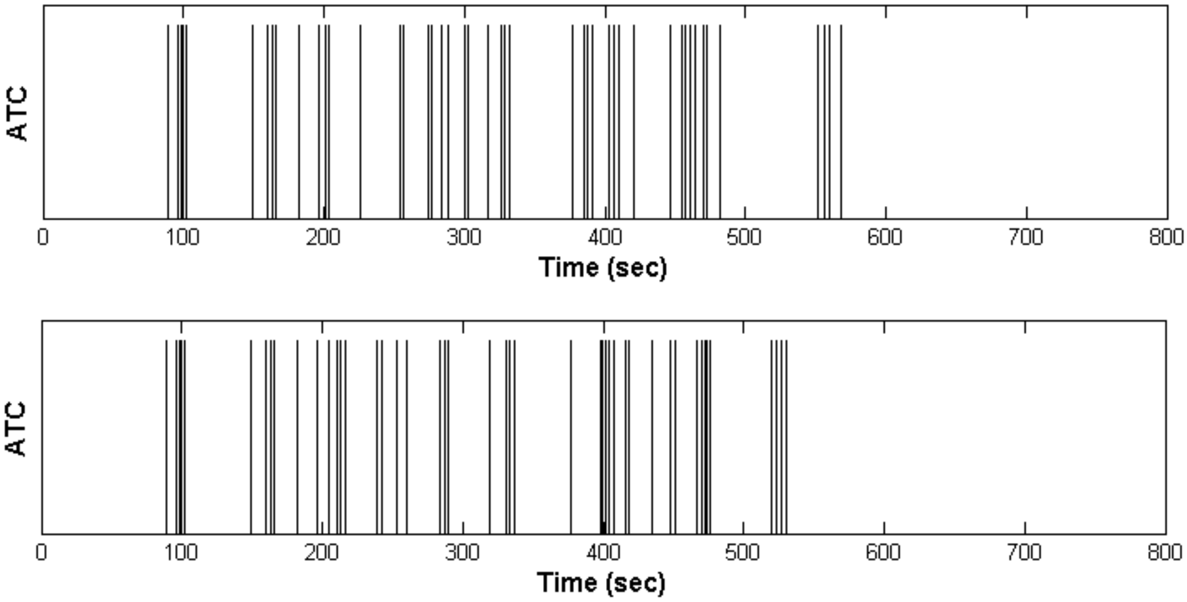

Figure 7: Time traces of information requirements for the air traffic control with FA6 in the nominal (top) and non-nominal (bottom) scenario.

- Examining how an expert human agent might be reasonably expected to adapt to her/his task load. For example, by associating a duration and priority to each action, the agent can keep track of how many actions are currently "in its queue" and possibly delay or interrupt lower priority actions.
- Using the specification of information transfer requirements to explicitly model various mechanisms for this transfer. For example, some information transfers may be sufficiently unusual or require negotiation to the extent that they merit direct human-to-human communication, which can be modeled as additional actions allocated to the agents and included in measures of their task load. Likewise, some information transfer mechanisms may inherently add some latency or error, which could then impact the behavior of the receiving agent and their contribution to the concept of operation.
- Examining the sensitivity of the concept of operations to predictable human or system errors. For example, a human agent can be modeled as having some probability of forgetting to perform low-priority actions during periods of task saturation.

Finally, such studies of function allocation can be extended to also examine the allocation of responsibility. Of particular interest are mismatches between the allocation of authority to execute a function, and of responsibility for the outcome of the action. In such cases, further actions may be required in the model: the responsible agent may feel a need to monitor the agent with authority, and the agent with authority may be tasked with regular reporting. These actions themselves will add to the task load and information transfer requirements.

ACKNOWLEDGMENT

This work is sponsored by the NASA Aviation Safety Program with Dr. Guillaume Brat serving as Technical Monitor under grant number NNX13AB71A S04. The authors also thank the other WMC developers for their ongoing mutual support.

REFERENCES

[1] Pritchett, A., Kim, S., and Feigh, K., "Measuring Human Automation Function Allocation," *Journal of Cognitive Engineering and Decision Making*, Vol. 8, No. 1, 2014, pp. 52-77.

[2] Grimaud, I., Hoffman E., Rognin, L., and Zeghal, K., "Limited delegation with arrival streams: more insight on its impact on controller activity," *Conference on Guidance, Navigation and Control*, Monterey, CA, USA, 2002.

[3] Wing, D., et al, "Pilot and controller evaluations of separation function allocation in air traffic management," *10th USA/Europe Air Traffic Management R&D Seminar,* Chicago, IL, USA, 2013.

[4] Lee, P., et al, "Free Maneuvering, Trajectory Negotiation, and Self-Spacing Concepts in Distributed Air-Ground Traffic Management," *5th USA/Europe Air Traffic Management R&D Seminar,* Budapest, Hungary, 2003.

[5] Ruigrok, R., and Valenti, C., "The Impact of Aircraft Intent Information and Traffic Separation Assurance Responsibility on En-Route Airspace Capacity," *5th USA/Europe Air Traffic Management R&D Seminar,* Budapest, Hungary, 2003.

[6] Bigelow, M., "Examining the relative costs and benefits of shifting the locus of control in a novel air traffic management environment via multi-agent dynamic analysis and simulation." Masters' Thesis, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, USA, 2011.

[7] Pritchett, A., Feigh, K., Kim, S., and Kannan, S., "Work Models that Compute to Support the Design of Multi-Agent Concepts of Operation," *Journal of Aerospace Information Systems*, Vol. 11, 2014, pp. 610-622.

[8] Pritchett, A., Kim, S., and Feigh, K., "Modeling Human–Automation Function Allocation," *Journal of Cognitive Engineering and Decision Making*, Vol. 8, No. 1, 2014, pp. 33-51.

[9] Swierenga, K., "An Evaluation of Interval Management using Task Analysis and Work Domain Analysis," Masters' Thesis, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, USA, 2013.

AUTHOR BIOGRAPHIES

Martijn IJtsma is a graduate student at the TU Delft and a research intern in the Georgia Tech Cognitive Engineering Center in the School of Aerospace Engineering.

He specializes in human-machine interaction in complex systems design. He received his Bachelors in Aerospace Engineering from the TU Delft.

Jacco Hoekstra is full professor at the TU Delft and has obtained his MSc, PhD and a private pilot's license from the TU Delft. He has worked at the Dutch National Aerospace Laboratory NLR for 16 years. He co-operated with NASA, the FAA and many European organizations. The topics of his ATM research include 4D Trajectory based ATM, airborne separation assurance and controller-pilot data link communication. He founded the Association for Scientific Development of ATM, was the founding director of AT-One and the head of NLR's Air Transport Division.

He has served two terms as Dean of the Aerospace Engineering faculty of the TU Delft and he now holds a chair in CNS/ATM in the Control & Simulation section. Next to his research, he currently teaches CNS/ATM, Programming in Python and Aeronautics.

Raunak Bhattacharyya is a graduate research assistant in the Georgia Tech Cognitive Engineering Center in the School of Aerospace Engineering.

He specializes in modeling and simulation of expert performance in complex work environments. He received his Bachelors in Aerospace Engineering from the Indian Institute of Technology. He is a student member of the AIAA.

Amy R. Pritchett is the David S. Lewis Associate Professor in the Georgia Tech School of Aerospace Engineering, and Director of the Cognitive Engineering Center.

She specializes in designing to support the human contribution to safety in aviation. She has also served as Director of NASA's Aviation Safety Program. She received her ScD, SM and SB from MIT's Department of Aeronautics and Astronautics. She is a member of the HFES and editor in chief of its Journal of Cognitive Engineering and Decision Making. She is an associate fellow of the AIAA and senior member of the IEEE.