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Martijn Ijtsma

Amy R. Pritchett

Raunak P. Bhattacharyya

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Martijn Ijtsma
Delft University of Technology
Delft, the Netherlands

Amy R. Pritchett and Raunak P. Bhattacharyya
Georgia Institute of Technology
Atlanta, GA USA

Authority-responsibility mismatches are created when one agent is authorized (has authority) to perform an activity, but a different agent is responsible for its outcome. An authority-responsibility mismatch demands monitoring by the responsible agent that itself requires additional information transfer and taskload. This paper demonstrates a computational simulation methodology that identifies when mismatches will occur in complex, multi-agent aviation operations, and their implications for information transfer between agents and task demands on each agent. A case study examines 25 authority and responsibility allocations in a NextGen/SESAR scenario in a terminal area where authority and responsibility for activities involving optimal profile descents, merging and spacing can be fluidly allocated to the aircraft (pilot/flight management system) or to the ground (air traffic controller/controller decision aids and automation).

Human factors needs to be involved early in design. We propose the early intervention of analyzing for, and preventing, air traffic and flight deck concepts of operation that place unreasonable demands on any agent, particularly the pilot and/or air traffic controller. Such demands may include requiring too much taskload, or assigning tasks that require substantial information transfer between agents, or implicitly creating additional monitoring tasks.

A concept of operation defines which actions must be performed in complex multi-agent systems and which agents – human or automated – have authority and responsibility to perform these actions. In this paper the following definitions are used: *Authority* is the requirement for an agent to execute a task, and *Responsibility* is the designation of accountability for the outcome of a task, in an organizational, regulatory and legal sense. Authority and responsibility do not always need to be aligned. Authority-responsibility mismatches, as first identified by Woods (1985), occur whenever one agent is authorized to execute a task, but a different agent is responsible for the outcome. As a result of the mismatch, the responsible agent needs to get information about the task outcome (and perhaps performance), monitor the authorized agent, and perhaps intervene. Thus, when the function allocation within a concept of operation generates authority-responsibility mismatches, it also implicitly creates additional information transfer and monitoring-taskload beyond that visible when only the authority allocation is examined.

Feigh and Pritchett (2014) distinguish between taskwork (required to achieve common work goals regardless of function allocation) and teamwork (required to coordinate between agents within a specific function allocation). Function allocation methods to date typically look at the allocation of authority, typically focusing on the taskwork (e.g. Wing et al., 2010; Scallen & Hancock, 2001), but the allocation of responsibility must also be considered to properly predict the teamwork demands that will emerge during the actual operation. This teamwork includes the information transfer and monitoring resulting from authority-responsibility mismatches.

Predicting the demands on any person in a novel, complex, multi-agent concept of operation is difficult. For example, earlier studies have shown that, in a chain of aircraft performing flightdeck interval management, the timing of information transfer and taskload changes from the first aircraft in the chain to subsequent aircraft that have to respond to the aircraft ahead of them (IJtsma, Bhattacharyya, Pritchett & Hoekstra, Submitted; Bhattacharyya & Pritchett, 2014). Thus, in this paper we demonstrate how simulation can predict such emergent effects. Here, we focus on authority-responsibility mismatches and their commensurate task load. We demonstrate the general method in the specific context of a terminal area where 25 different allocations of authority and responsibility are fluidly made for activities involving optimal profile descents, merging and spacing, changing whether they are allocated to the aircraft (pilot/flight management system) or to the ground (air traffic controller/decision aids and automation).

Computational Simulation of Authority and Responsibility Allocation

Work Models that Compute (WMC) is an open-source simulation platform written in C++ that can dynamically model complex, multi-agent concepts of operation (Pritchett, Feigh, Kim & Kannan, 2014). WMC is unique in the sense that the model of work is independent of the agent models, allowing for the fluid allocation of activity to different agents.

Work models describe the collection of tasks that together achieve common goals. The tasks are modeled such that each represents an action that can be completed by a single agent at a single point in time. In this case study, to isolate the effect of function allocation, actions are executed the same way regardless of the authority allocation. Additionally, to isolate the demands placed on each agent by the function allocation, actions are executed without errors and delays. After this preliminary evaluation, more detailed analysis can evaluate human performance in the concept of operation (Pritchett, Feigh, Mamessier & Gelman, 2014).

A function allocation is represented by which actions are allocated to which agents for both authority and responsibility in any simulation run – or at any particular instant within a run. Mismatches in authority and responsibility manifest themselves through extra monitoring actions. In real operations these monitoring actions are created implicitly when the need for them emerges; correspondingly, they are created automatically during a simulation whenever the simulation framework detects an authority-responsibility mismatch. In this paper the monitoring actions are empty placeholders that serve to identify taskload and information transfer requirements, but the simulation framework also allows for any action to specify functions that represent more elaborate monitoring activities appropriate to its own situation.

Table 1.
Authority and responsibility allocations (A = Air, G = Ground).

Functional blocks	Authority allocations (AA)					Responsibility allocations (RA)				
	1	2	3	4	5	1	2	3	4	5
Vertical profile control	G	A	A	A	A	G	A	A	A	A
Aircraft configuration management	G	A	A	A	A	G	A	A	A	A
Lateral control	G	A	A	A	A	G	A	A	A	A
Speed control	G	G	A	A	A	G	G	A	A	A
Lateral profile management	G	G	G	A	A	G	G	G	A	A
Vertical profile management	G	G	G	G	A	G	G	G	G	A
Speed management	G	G	G	G	A	G	G	G	G	A
Non-nominal situation management	G	G	G	G	A	G	G	G	G	A

WMC logs the exact time instances when an action is performed, and the executing agent for that action. Additionally, the simulation logs any time instances when an agent requires knowledge of information that is set by a different agent: these instances reflect a requirement for information transfer, and are from here on referred to as information transfer requirements.

Case Study

This case study builds on an earlier study of authority allocation between air- and ground-based operators in a NextGen/SESAR terminal area (IJtsma et al, 2014). Three aircraft are arriving into Schiphol Airport RWY18R with the lead aircraft performing an Optimum Profile Descent (OPD) and subsequent aircraft performing in-trail and merging interval management (IM). One aircraft enters the airspace from the West and initially performs an OPD along the RIVER arrival route. Two other aircraft enter from the East and follow the ARTIP route, where the first aircraft initially performs an OPD and the second aircraft follows at a 60 second time interval through IM. The two traffic streams later merge. An off-nominal situation can be introduced wherein the RIVER aircraft requests priority to land (e.g. medevac flight) and the other two aircraft need to maneuver to sequence behind it at the merge point. Thus, four agents are simulated: the three flight crews (FC) and one air traffic controller (ATC). The agent models are deliberately “perfect” in that they execute actions immediately and without error, so that any concerns with the underlying concept of operation can first be clearly isolated.

The model groups similar actions together into functional blocks (IJtsma et al., 2014). The functional blocks are allocated to either the FC or ATC agents. Five authority (AA) and five responsibility allocations (RA), both conventional and non-conventional, are analyzed, as shown in Table 1. Each authority allocation is tested with each responsibility allocation, thereby resulting in 25 complete function allocations. Monitoring actions are automatically spawned whenever an authority-responsibility mismatch is present and is assumed to be perfect in the sense that whenever an action is executed, the responsible agent will instantly monitor the executing agent.

Results

To illustrate the detailed analysis that WMC affords, Figure 1 shows an action time trace for the air traffic controller with AA3 and RA2. The ATC agent experiences high task load in peaks, particularly between 350 and 480 seconds into the simulation. Additionally, there are three moments in time when heavy monitoring is required, starting at 100 s, 180s and 480 s.

To provide more aggregate results, summing up all taskwork and monitoring actions within each combination of allocations of authority and responsibility results in Figure 2. As may be predicted, increasing authority allocation to the flight crew results in a higher task load for the flight crews and a lower task load for the ATC agent. The monitoring required of each agent, on the other hand, results from the combination of allocations of authority and responsibility: where mismatches occur, monitoring results. Put together, the total demands on the agent – explicit taskload and implicit monitoring – is driven more by responsibility allocation than by authority.

Similarly, Figure 3 shows the total amount of information transfer, discriminating between transfers stemming from taskwork versus monitoring. A wave pattern can be observed in the information transfer stemming from the taskwork, wherein authority allocations that divvy up the work equally between air and ground result in high information transfer wherever their assigned actions need to coordinate; conversely, an agent that is allocated authority for everything doesn't need to ask for information set by others' activities. On the other hand, information transfer for monitoring shows a similar trend as the taskload results in Figure 2: it is driven by mismatches.

Conclusion

This paper demonstrates that function allocation should not just consider the distribution of authority, but also of responsibility, particularly to identify authority-responsibility mismatches. These mismatches implicitly create additional monitoring tasks for the responsible agent, and should be included in human factors analysis. Thus, computational simulation of concepts of operation can provide quantitative insight in the task load, monitoring and information transfer demands resulting from function allocations, including authority-responsibility mismatches.

This methodology can be used to objectively assess function allocations early in the design process and subsequently guide the further design of the concept of operation to prevent human performance issues. These results, thus, can highlight situations where a so-called "human factors issue" is actually inherent in a concept of operation, regardless of training or

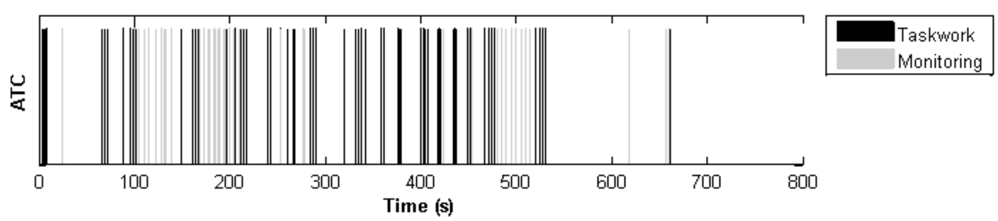

Figure 1. Action time trace for the ATC agent with AA2 and RA3.

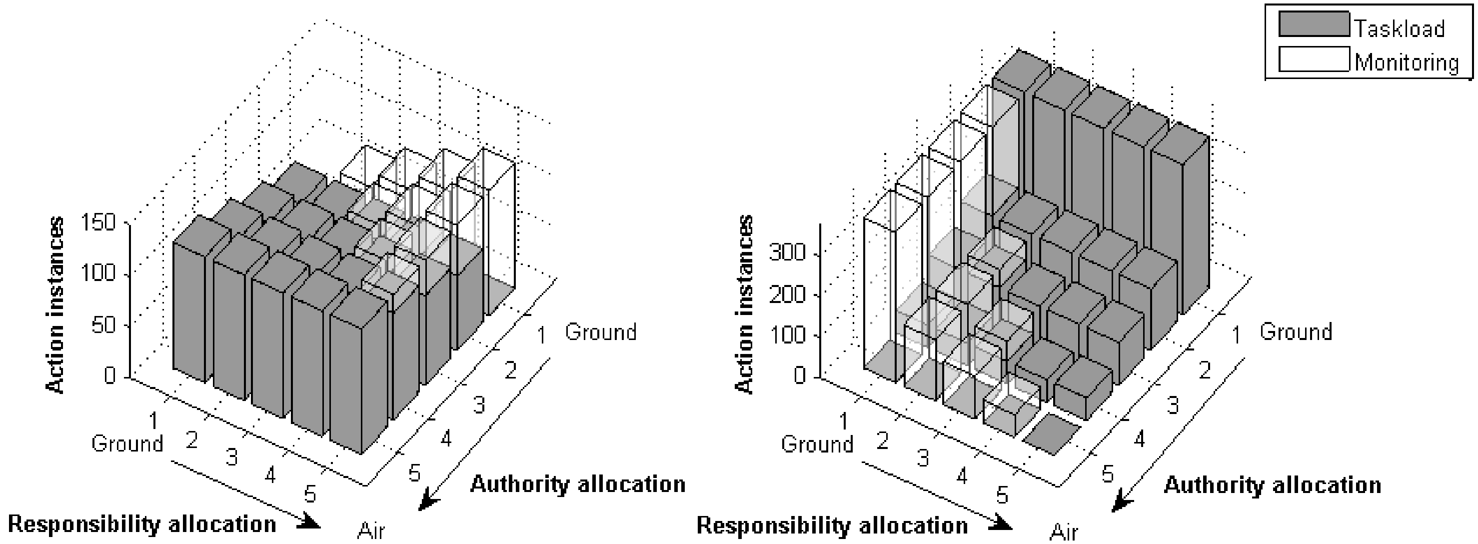

Figure 2. Total taskwork and monitoring actions for (left) averaged over the three flight crew agents and (right) the ATC agent.

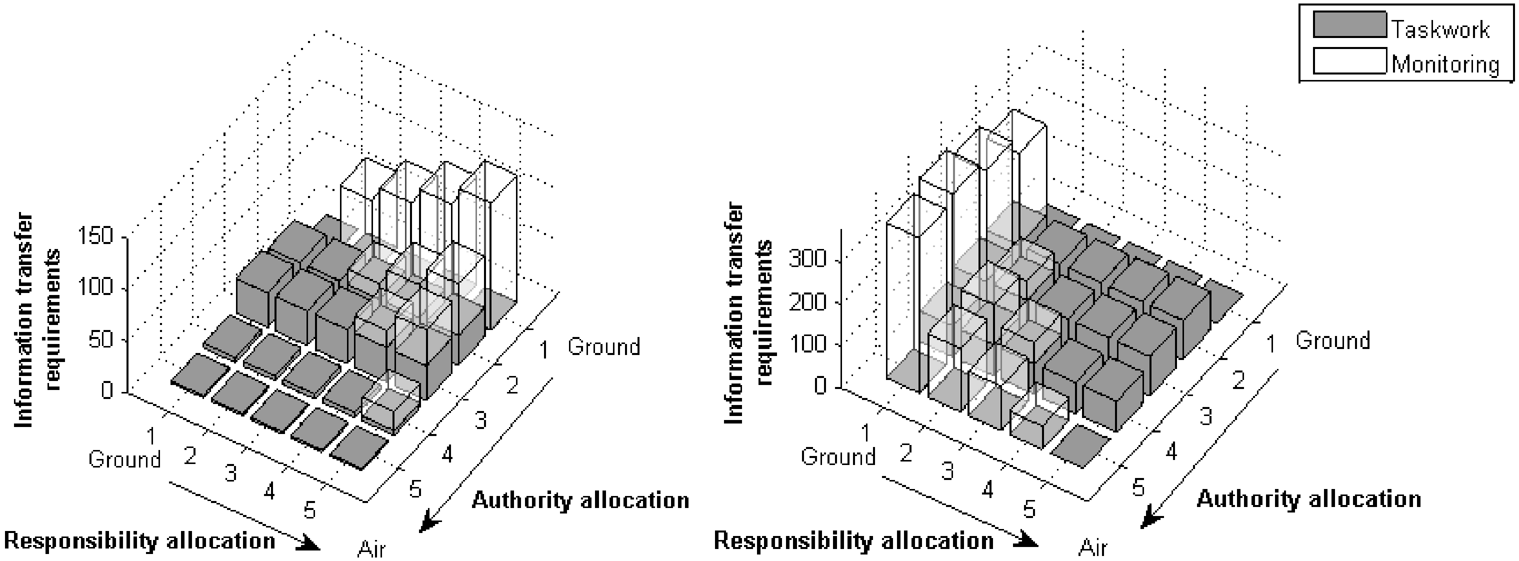

Figure 3. Information transfer requirements for (left) averaged over the three flight crew agents and (right) the ATC agent.

operator capability – we hope also that such issues can then be designed out of the concept of operation before it is entrenched through the implementation of automation and interfaces that are costly to re-design.

Once this fundamental assessment is performed, subsequent computational simulations can also examine human performance issues in greater detail. For example, different methods for performing each task can be examined, and the sensitivity of the operation to response time or variation in performance analyzed in detail.

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