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Abstract

Within Human Factors Engineering, a decision-making process called function allocation (FA) is used during the design life cycle of complex systems to distribute the system functions, typically identified through a functional requirements analysis, to all human and automated machine agents (or teammates) involved in controlling the system. Most FA methods make allocation decisions primarily by comparing the capabilities of humans and automation, and then by considering secondary factors such as cost, regulations, and the health and safety of workers. The primary analysis of the strengths and weaknesses of humans and machines, however, is almost always considered in terms of individual human or machine capabilities. Yet, FA is fundamentally about teamwork in that the goal of the FA decision-making process is to determine the optimal allocations of functions among agents. Given this framing of FA, and the increasing use of and sophistication of automation, there are two related social psychological issues that current FA methods need to address more thoroughly. First, many principles for effective human teamwork are not considered as central decision points or in the iterative hypothesis and testing phase in most FA methods, despite the fact that social factors have numerous positive and negative effects on individual and team capabilities. Second, social psychological factors affecting team performance can be difficult to translate to automated agents, and most FA methods currently do not account for this effect. The implications for these issues are discussed.

Keywords: Function allocation; Automation; Team dynamics; Human-automation team performance

1. Introduction

Function Allocation (FA) is a human factors engineering (HFE) decision-making process and method that is used during the design life cycle of complex systems to distribute the system functions, typically identified through a functional requirements analysis (FRA), among all agents in a team, namely humans and automated systems. The function can be assigned to a human or automation agent, or to a multi-agent team (e.g., comprised of automation and human(s), a team of human agents, or a team of automation agents). As a part of the systems engineering approach to designing complex systems, FA essentially analyzes and verifies that the functional requirements identified in the FRA are sufficiently well defined to be implemented in an operational concept. This is an important step in the HFE process in that the appropriate allocations of functions to agents in complex systems, such as nuclear power plants, is an essential component to the effective and efficient design and conduct of operations.

FA has a long history in the field of HFE. The earliest research in this field began in the 1950's with the advent of what is now commonly referred to as Fitts' List (Fitts, 1962), which describes what "Humans are Better At" versus what "Machines Are Better At" (i.e., automation). The list has been used (many human factors experts would argue incorrectly) as a simple decision aid to assign the functions to human operators or automation, depending on what agent the analysts believed would be better able to perform the function. Using Fitts' List as a starting point, other researchers have tried to improve the technical basis for FA methods. By far the most detailed guidance and approach to FA is NUREG/CR-3331 (Pulliam, Price, Bongarra, Sawyer, & and Kisner, 1983). The key notion expressed in NUREG/CR-3331, is the allocation decision matrix shown in Fig. 1.

NUREG/CR-3331 explains this matrix by first describing the two regions: U_a (unacceptable: automation), and U_h (unacceptable: human). Functions falling in region U_a are too low on the "machine performance" scale to be considered for automation; they can presumably be allocated to the human by default. Conversely, in region U_h, any allocation will presumably be to machine. However, at the intersection of U_a and U_h is the region U_{ah}, where both humans and machines perform unacceptably. Any function that falls in this region should be considered for redesign or included in a system only as a final resort.

The regions P_h and P_a represent functions that might be acceptably performed by either human or machine, with varying degrees of advantage. In the region P_h (preferred: human), the human is expected to be substantially superior as a control component. Functions in this region will be allocated to humans in the absence of other overriding considerations. Conversely, in the region P_a (preferred: automation), allocation will ordinarily be to machine.

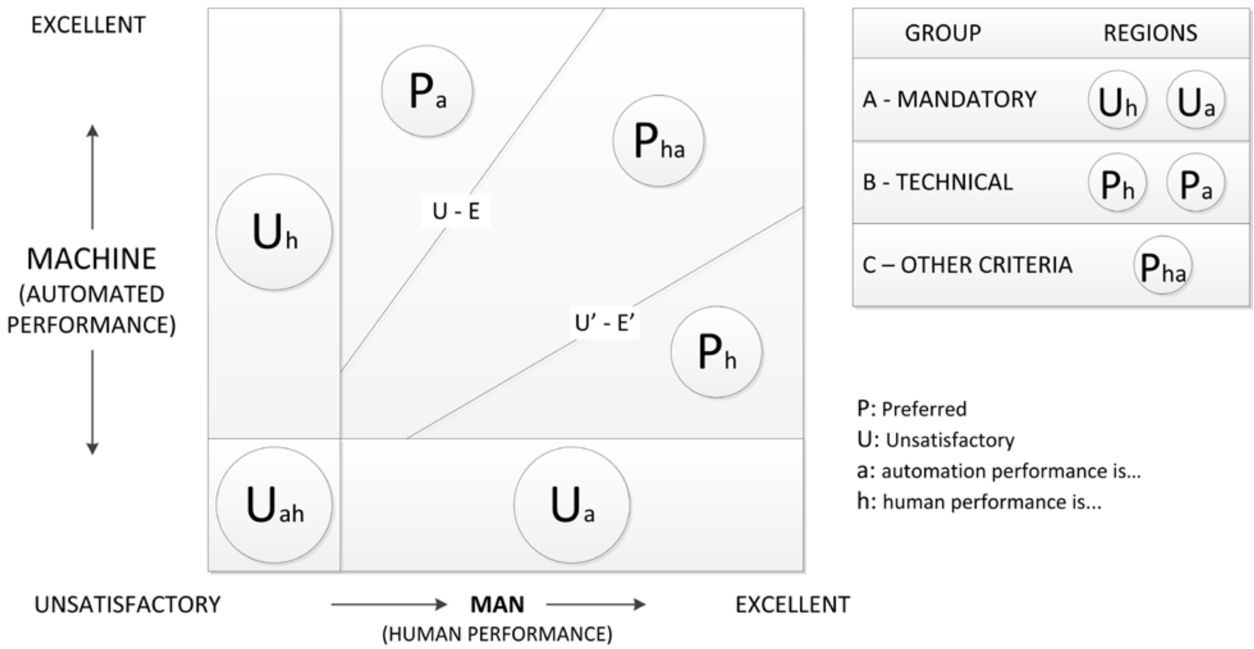

Fig. 1. Allocation Decision Matrix from NUREG/CR-3331 (Pulliam, Price, Bongarra, Sawyer, & and Kisner, 1983).

Then there is the region P_{ha}, bounded by regions P_a, P_h, U_a, and U_h, and by the lines of constant proportional difference U-E and U'-E'. At all points in this region the difference between the expected performance of human and machine is not great. This is a region of less certain choice so far as the relative control performance of human and machine is concerned. In this region the allocation decision can be based on considerations other than the engineering performance of human and machine as control components. The considerations include costs, worker preferences, and the availability of proven design experience.

One important additional concept expressed in NUREG/CR-3331 is the notion of formulating allocation hypotheses (i.e., solutions) and testing them iteratively until optimal solutions are found. As the authors of NUREG/CR-3331 state: “The designers formulate a hypothesis concerning the engineering solution, the allocation of functions, and the human solution. They then test these hypotheses in a number of ways. They test for completeness and consistency of the match between engineering and human solutions, for engineering and human factors feasibility, for consistency between subsystems, for cost, and by system simulation or other empirical tests. More often than not, these tests reveal weakness or error in the initial hypothesis. Cycles of hypothesis and test continue until a sufficient system-wide set of hypotheses is achieved.” (pg. 18). This iterative hypothesis testing does not explicitly consider social psychological factors, or more specifically, how team dynamics may affect the efficacy of the allocation solution.

Many other researchers have since used Fitts’ List and NUREG/CR-3331 as the starting point for further refinements of approaches to FA. For example, Bastl et al. (Bastl, Jenkinson, Kossilov, Olmstead, Oudiz, & Sun, 1990), recognized that automation was going to play a larger role in the operation and control of nuclear power plants, and that FA methods needed to be updated to address this fact. Interestingly, this method is the only refinement that explicitly identifies social issues as one of many influencing factors that FA should consider. Mersiol (Mersiol, 2001) developed a practical methodology based on NUREG/CR-3331 for the re-allocation of functions when modernizing existing designs. More recently, a trio of articles by Pritchett, Feigh and Kim has elucidated a set of requirements for FA (Feigh & Pritchett, 2014), a modeling framework for FA (Pritchett, Kim, & Feigh, Modeling Human–Automation Function Allocation, 2014), and a set of metrics to evaluate FA decisions or solutions (Pritchett, Kim, & Feigh, Measuring Human-Automation Function Allocation, 2014). By posing and then using the requirements, modeling framework, and metrics in an integrated fashion, these researchers developed a comprehensive and robust FA method that can be used to evaluate FA solutions. Finally, Hanes, Fink, and Naser (Hanes, Fink, & Naser, 2015) developed a human-automation FA method because they recognized that the modernization of control rooms would undoubtedly include automation that would provide enhanced capabilities, and FA was a tool to address how to take full advantage of automation's capabilities.

A consistent theme in virtually all of the FA work since NUREG/CR-3331 is that FA methods need to be updated because some nuclear power plant are being modernized and automation is playing a larger role in the control room. Sheridan (Sheridan, 2002) elucidated this issue when he demonstrated that human cognition and level of automation interact to produce different outcomes depending on the nature of their interaction. From the perspective of cognitive psychology's concept of information processing, humans (in this context, nuclear power plant operators) progress through different stages of cognitive processing as they execute their tasks in the control room. Sheridan called these cognitive processing stages: acquire information, analyze and display, decide action, and implement action. He also recognized that the amount of automation used in a given situation could vary from fully manual to fully automatic, with intermediate levels in between. He then demonstrated that across different systems (e.g., air traffic control, automated manufacturing, etc.), in order to allocate functions effectively between operator and automation, the designers needed to know the operator's cognitive processing stage in order to determine what level of automation would be most appropriate to execute a given function.

2. The importance of social dynamics in teamwork

While these advancements in FA to address the increased used of automation and modernization are valuable and improve the state of practice, they are not without issue. One in particular, previously identified in Hugo et al. (Hugo, Gertman, Joe, Medema, Whaley, & Farris, 2013) is that FA not only needs to consider the individual cognitive and computational capabilities of humans and automation, but also social factors that affect teamwork. Failing to consider social factors such as team dynamics in FA decisions can lead to difficulties in anticipating how the operational context will affect the ability of agents to perform their functions. That is, the roles and responsibilities assigned to humans and automation to perform system functions are always contextually dependent. There are a host of social factors that can positively and negatively affect an individual's and a team's ability to perform their assigned function. For example, many individual human capabilities are improved when agents work as a team. Similarly, some principles of human teamwork (e.g., Leadership skills), which improve human individual and team performance, are unlikely to affect the performance of automated agents, and the absence of this team dynamic may affect the human agents and overall system performance. There are a number of everyday examples where the introduction of automation into human teams had disruptive effects on teamwork and the assignment of roles and responsibilities. In short, FA methods still do not effectively factor in the emergent social dynamics that arise when agents interact during normal, abnormal, and emergency operations.

3. Social factors that affect function allocation

This section provides some examples of how social factors can affect FA decisions. In general, most of the social factors stem from fundamental human frailties that define a large part of what it means to be human. Humans have beliefs, motivations, and emotions that affect their performance. Moreover, these are frailties that automated agents do not necessarily share, which introduce an entirely different set of problems for teamwork and FA decisions. As such, for each example, the social factor is described briefly, and then the implications it has on FA decisions for both human teams and human-automation teams are provided. Note that neither the list of social factors nor the implications provided are exhaustive. Rather, the social factors described are a subset of more complete lists that can be found in Joe et al. (Joe, O'Hara, Medema, & Oxstrand, 2014) and O'Hara and Joe (O'Hara & Joe, 2014), and the implications are merely meant to provide a counterexample to the general assumption in most FA methods that social factors do not significantly affect allocation decisions.

3.1. Belief in the concept of team

Effective human teams have individuals that believe in (or they are told that their compensation depends on) the idea that there is a mutual benefit to working together (i.e., that what binds them together is greater than what drives them apart, and that if they act on that belief they will achieve better results than if they were working separately). Dickinson and McIntyre (Dickinson & McIntyre, 1997) referred to this as "team orientation," which relates to whether team members have positive or negative attitudes towards each other, the leader, and their task(s) and whether each individual believes it is worthwhile to stay in the group or leave.

Most FA methods assume that human agents will work well as a team, but groups of people tend to work as teams only under specific circumstances. Larson and LaFasto (Larson & LaFasto, 1989) explicate a number of these circumstances, including the presence of a clear and elevating goal that cannot be easily achieved without the coordinated efforts of multiple individuals. If these social circumstances are not met, the team will likely not work well together, and the actual performance of the human team may be well below the expected level of performance predicted or anticipated by the FA analysis. Furthermore, this discrepancy may not get resolved adequately in the iterative hypothesis testing phase of many FA methods because social factors are not a central criteria used to judge the adequacy of the allocation (i.e., "Goodness of Allocation"). A significant unresolved variance between the actual and expected level of performance may jeopardize the larger concept for the plant's operations, particularly if the human team is assigned to perform a mission critical function with many other functions dependent on it.

Another implication for FA is how this social factor does not apply to automation. Automation agents have no beliefs, sense of responsibility, conflict resolution, or need for social acceptance. An automation agent's behavior or performance does not change with an appeal to a belief in the concept of team. It cannot work more or less than its predetermined programming. This difference between how automation and humans are affected by this social factor needs to be considered when FA methods are distributing functions among agents.

3.2. Trust

Effective teamwork requires trust in the individual members of the team. Lee and See (Lee & See, 2004) defined trust as "…the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and variability". The level of trust among human teammates, however, is rarely considered in most FA methods. Teams of humans that do not trust each other will perform more poorly than FA analysts may presume when deciding to allocate a function to them, thus leading to a sizable discrepancy between the team's anticipated and actual capability to execute the function.

Additionally, trust in automation is a well researched issue in human factors, which has been repeatedly identified as a contributing factor to explain why automation, when applied to solve an HFE problem, often leads to lower overall system performance. Analysts considering FA solutions involving a shared function between humans and automation should be mindful of how the human's lack of trust in poorly designed automation may decrease the likelihood that that function will be executed properly.

3.3. Effective communication

High performing teams communicate effectively. Communication is the central behavior team members engage in to function as a team. It is central to:

- Exchanging information
- Establishing team situation awareness
- Coordinating and regulating individual efforts (i.e., communication links monitoring and feedback on other members' performance)
- • Building trust among team members (e.g., inaccurate, confusing, and/or erroneous transmissions, and/or difficulties in comprehending or interpreting the information transmitted can decrease trust).

As before, most FA methods do not explicitly include this factor in their decision-making and/or testing processes to distribute functions. However, there may be circumstances when human teams do not perfectly follow all best practices in communication. For example, if the successful execution of the function depends heavily on effective communication, and the circumstances where that communication occurs is under extreme time pressure or during highly repetitive routine situations, humans may not perform the function as well as expected. Yet, there is often no specific guidance in FA methods to inform the analysts of how communication may affect team performance.

From the perspective of allocating functions between humans and automation, effective communication has been identified as an important factor in how well humans and automation collaborate. Communication does not flow as naturally between humans and automation as it does between humans, since the human computer interface is, relatively speaking, clumsy and often disruptive. Furthermore, communication and other interactions between the human and automation agents can be very limited when the level of automation is high.

3.4. Team leadership

Effective teams have good leadership. Strong leadership by individuals formally appointed as leaders, and informal leadership by other team members, is well established as a key component to teamwork. Larson and LaFasto (Larson & LaFasto, 1989) argue that good leadership is principled and consistent, and has both transactional (i.e., the management of subordinate team members through monitoring performance against criteria defined in formal work agreements), and transformational (i.e., leading the team by creating a vision and inspiring team members to strive for higher level goals) qualities. Furthermore, they argue that leaders who do not let their personal egos overshadow the contributions of the rest of the team tend to be more effective than those who take more than their share of the credit and less than their share of the blame.

As before, while most FA methods do not explicitly include this factor in their decision-making processes, there are circumstances where team leadership can affect the successful execution of a function assigned to humans. For example, if the function is assigned to the human team because it is required by regulations, but there is a failure in leadership that causes the team not to work together effectively, then the function will likely not get executed properly, and system performance may decline.

From the perspective of FA for automation, there is no concept of leadership in automation agents. They are indifferent to the quality and style of leadership. So, the fact that leadership style and quality affects humans means that FA for human-automation teams should factor in this difference when making allocation decisions. For example, if automation is ever in a leadership position, it is unlikely that the automated leader will effectively convey the leadership soft skills that would improve the morale and trust of the human subordinates.

3.5. Performance monitoring and feedback

Effective teams monitor and provide feedback on both overall group performance and individual contributions. The popular management maxim, “If you can’t measure it, you can’t improve it,” relates to the idea that monitoring team performance is a prerequisite to providing feedback on performance. Feedback is key to learning and the systematic adjustment of coordinated team activities that are needed to change to system-level process parameters (that are within the span of control of operators), which are necessary to achieve the desired process outcomes (e.g., operate the NPP safely and generate electricity profitably). Monitoring individual contributions to overall performance is also key to mitigating a well-known social psychological phenomenon called social loafing, where individuals working in groups tend to ride on the coattails of the collective team performance by putting forth less individual effort than they would if working alone or if their individual work contributions could be measured (Latané, Williams, & Harkins, 1979). Furthermore, both the communication and team leadership principles have an element of monitoring and providing feedback on performance. Team leadership is the principle that gives the authority to the leader to monitor and provide feedback on the performance of others on the team, and communication is the means through which feedback on the activities performed by the subordinate and monitored by the supervisor is conveyed to the subordinate.

If a function is assigned to a team (e.g., because it requires heuristic and/or inferential knowledge and human flexibility), and the human team has trouble following prescribed operational guidance on maintaining accountability amongst each other, the team may fail at executing that function. Moreover, this kind of failure (i.e., failure due to poor team dynamics) would not be detected or accounted for in most FA methods because social factors are not central to the initial allocation decisions or the iterative testing of allocations. If FA methods more explicitly included social factors, it may prompt decision-makers to make a different allocation of certain critical system functions that may be susceptible to breakdowns in human team, or human-automation team, performance.

With respect to automation and performance monitoring and feedback, even with well-designed human system interfaces, there is a limited ability for both human and automated agents to know and anticipate the other's intentions, actions, and how they may relate to the overall team and system goals. An FA analyst who decides that a system function should be shared between humans and automation, but does not factor in this difficulty, will likely discover during the initial startup of operations that the execution of the shared function is not as good as anticipated, and depending on the importance of that shared function, may significantly degrade overall system performance.

3.6. Coordination and assistance

Effective teams are well coordinated and provide assistance to one another. When this happens, performance above and beyond what each individual could achieve on their own can be realized. As Dickinson and McIntyre (Dickinson & McIntyre, 1997) put it, "Successful coordination implies the effective operation of other components of teamwork (e.g., communication, monitoring, and backup). In this way, the actions of individual members are merged to produce synchronized team performance" (pg. 22). Included in the principle of coordination is the extent to which team members have overlapping capabilities and are willing and able to seek and provide assistance to one another (i.e., provide redundancy or defense in depth) and increase overall system resiliency.

If an individual in a human team is supposed to coordinate their function with another individual (e.g., feed and bleed), or has the responsibility to provide assistance to another, but loses situation awareness or becomes distracted, the team's ability to execute that function becomes impaired relative to what the FA method estimated a priori as an acceptable level of human capability to perform the function. Additionally, automated agents have limited flexibility in knowing when the human teammate needs additional assistance, and overall, automation has a limited ability to redirect their activities and adapt to the shifting needs of the team, or to novel situations that are outside the boundary conditions defined in its programming.

3.7. Awareness of performance shaping factors

Effective teams are aware that personality traits and cognitive abilities can vary from person to person. How the team leverages, and not just manages, individual differences to enhance team performance is an important determinant in overall team performance. Similarly, external performance shaping factors (PSFs), such as task complexity, time pressure, and information/knowledge uncertainty can affect the team's ability to collaborate on functions assigned to them, which in turn can affect overall system performance. As such, an FA analyst is likely to overestimate a human team's ability to perform the function allocated to them if they are oblivious to, or discount, the effect of internal and external PSFs on human performance.

In contrast, automation agents do not feel anxiety (i.e., internal PSFs), time pressure (i.e., external PSFs), or the interaction of multiple PSFs in the same way humans do. Automation's performance is unaffected by these PSFs that greatly affect human performance. Finally, one paradox of using automation is that poorly designed or implemented automation can increase workload on humans, particularly when required to interact frequently with automation. Not appreciating these facts about automation in FA analyses will also result in different, but nevertheless, sub-optimal allocations.

3.8. Creating shared mental models

Effective teams recognize that, despite efforts to create accurate mental models, everyone has an idiosyncratic mental model of their environment, and that each team member must clearly communicate their mental model to others. That is, humans construct their knowledge of the world based on an attentionally constrained ability to detect and process external stimuli, and a less than perfect long-term memory system, which leads to the formation of an idiosyncratic understanding (i.e., mental model) of the situation. Furthermore, humans have difficulty communicating or sharing their mental models with other humans such that they and one or more team members are subsequently "on the same page of the playbook."

An example of how this social factor can affect a human team's ability to perform their assigned function in ways that most FA methods currently do not account for can be seen when different operators have different mental models of the plant's state even though they are all looking at the same objective indications. This situation may arise, for example, when a novice and expert try to diagnose the same plant abnormal condition. This problem is exacerbated when considering human-automation teams in that it often becomes even more difficult to establish a shared mental model or shared understanding of the situation.

4. Conclusion

FA ultimately is about optimizing the teamwork of agents to successfully execute the system functions allocated to them so that higher order goals can be achieved. This paper presents numerous examples to demonstrate how social factors can have deleterious effects on the performance of human teams and human-automation teams. Thus, in order to optimize team performance, FA methods need to consider both 1) the individual cognitive and computational capabilities of humans and automation, and 2) social factors that affect teamwork. In short, all system functions are executed in context dependent situations. Teamwork among agents in complex socio-technical systems will inevitably involve the interaction of individual cognitive and computational capabilities with the social context. This interaction is essentially an engineering and humanistic challenge. We suggest that the field of HFE should consider reconceptualizing how we think about and conduct FA to better address this interaction between engineering and humanistic problems.

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