Applying Mathematical Modeling Technology to the Study of Team Training and Performance

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ABSTRACT

Mathematical modeling technologies hold promise as an approach for providing training system designers with critical information regarding human behavior in complex systems. Such information is useful in researching training principles, defining instructional strategies, developing performance measures and establishing diagnostic and feedback mechanisms. An area that is particularly complex for training system designers involves multi-operator systems, where an understanding of individual human performance must be augmented by an understanding of team performance and functioning. To date, several approaches have been proposed to model team performance, but further methodological advances are needed. The purpose of this paper is to describe the use of Petri nets, a mathematical modeling technique, as a means to model complex team functioning and as a basis to develop team performance measures.

INTRODUCTION

The ability of military teams to reach high-quality tactical decisions is one of the most critical determinants of combat readiness and effectiveness. In the operational environment, such decisions must often be reached in situations characterized by: 1) severe time pressure, 2) complex, multi-component decision tasks, 3) rapidly evolving and changing information, 4) high short-term memory demands, 5) high information ambiguity, and 6) other types of stress such as fatigue or temperature extremes. In addition, tactical decision-making is most often accomplished via the coordinated effort of a team of operators. In fact, while final decision authority is usually retained by a single individual, such as the Captain of a war ship, this ultimate decision-maker is highly dependent on a team of individuals to provide timely, accurate situation assessment information in support of the final decision.

In a typical Navy combat information center (CIC), for example, large amounts of information from a variety of sources must be perceived, processed, integrated and transmitted in support of a tactical decision. These activities are carried out by a hierarchically structured team of operators, each of whom performs individual functions that are critical to the final decision. In such a situation, team members must not only perform their individual tasks effectively, but must also coordinate activities and inputs so that the ultimate decision-maker receives an accurate, timely assessment of the situation upon which to base his decision. In fact, the efficacy of the ultimate decision-maker in this context is dependent as much on the quality of situation assessment information provided by the team as it on his own decision-making ability.

For this reason, efforts to improve performance in many tactical environments must focus attention on both the capability of the individual decision-maker as well as the team which provides support. By the same token, measuring the performance of decision-making teams must be directed toward assessing the team's contribution to the decision and decision process as well as evaluating the performance of the ultimate decision-maker. Without attention to both "levels" of measurement, it is impossible to determine where the decision process degraded, who was responsible for errors, or how to improve performance in the future. This requirement suggests that an understanding of effective teamwork and team process must be developed so that specific teamwork behaviors necessary for effective performance can be identified. Once accomplished, critical team process behaviors can be operationalized in a manner that allows evaluation of team performance.

The purpose of this paper is to describe a mathematical modeling technique (called Petri nets) that holds promise as a means to model team performance and serve as a basis for measuring team performance effectiveness. To accomplish this, the literature in team performance and team performance measurement will be briefly summarized. Next, the Petri net methodology will be explained, and finally, the potential benefits and advantages of employing Petri nets to the study of team performance will be delineated.

TEAM PERFORMANCE RESEARCH

Identifying Critical Teamwork Skills

Several researchers have suggested that teams comprise the cornerstone of modern American industry [1] [2]. It is not surprising, therefore, that work teams have been the subject of countless investigations over the past few decades. Despite this volume of research, however, relatively little is known about the nature of teamwork or how best to train teams to perform effectively [4]. In particular, past research has done little to identify specific teamwork skills or investigate how teams acquire, maintain and lose critical teamwork skills.

Recently, a series of studies conducted with military command and control teams and aircrews has made significant progress in understanding the nature of teamwork [5] [6] [7]. To begin with, Glickman et al. found that two separate tracks of behavior evolve during team training. The "taskwork" track involves skills that are related to the execution of the task and/or mission. The second track, labeled the "teamwork" track, involves skills that are related to functioning effectively as a team member. To summarize the overall findings of this and related work, the following conclusions can be drawn: a) behaviors that are related specifically to team functioning, regardless of the current task, are important to task outcomes [6] [7], b) effective teamwork behavior appears to be fairly consistent across tasks [6], c) team process variables such as communication, coordination, and compensatory behavior influence team effectiveness [7].

In terms of specific teamwork behaviors, McIntyre et al. [8] recently summarized the lessons learned from investigations of tactical teams and concluded that teamwork appears to be comprised of a complex of behaviors including: closed-loop communication, compensatory behavior, mutual performance monitoring, giving or receiving feedback, adaptability and coordination. Further, these authors suggest that in effective teams, members seem to be able to predict the behavior and needs of other members.

Measuring Team Performance

A related area of concern to those who study teams is how best to diagnose and measure team performance. Evidence presented above suggests that process measures such as communication and information flow, are a necessary adjunct to task outcome measures. This is particularly true when the purpose of measurement is to provide feedback that will improve performance. Outcome measures do not contain information that is useful for diagnosing the cause of poor performance, or describing how team members should adjust behaviors to affect improved performance in the future. For example, informing a team that they have misclassified a contact does not provide guidance that will enable them to perform successfully on that task in the future. On the other hand, informing them that their error was due to a specific breakdown in communication among two members gives them insight into how subsequent performance might be improved.

To date, several studies have indicated that communication behaviors and other process measures are related to team effectiveness [7] [9] [6]. For example, in a series of studies, Morgan and associates [10] [5] [6] constructed and refined a team performance observational scale. Using a critical incidents technique, these researchers interviewed team training instructors in order to generate behavioral examples of effective and ineffective teamwork. These items were then included as part of a checklist that was used by training instructors to rate teams in training. Evidence from these studies indicate that effective and ineffective teams could be distinguished based on the frequency of behaviors exhibited in various categories on the scale.

More recently, observational measures of team performance have been developed to assess the teamwork skills of cockpit crews [11]. Based on a needs assessment conducted with 134 helicopter pilots, an instrument is being developed that requires an observer to rate crews on critical teamwork skills that have been grouped into several behavioral dimensions. This is slightly different from the Glickman et al. [5] approach of recording behavioral frequencies. Preliminary evidence suggests that such a methodology can be successful in distinguishing effective from ineffective teams [7].

Other researchers have been concerned with developing measures of team communication as indicators of effectiveness. With respect to communication patterns, several investigators have found that overall frequency of communication among aircrew members is directly related to crew effectiveness [12] [13]. In addition, communication content has also been found to be related to aircrew effectiveness. For example, it has been found consistently that the frequency of commands, observations, suggestions and acknowledgements is positively related to performance [12] [14].

While the observational scales and

communication assessment techniques described above are useful as indicators of team performance, other measures of team effectiveness must be developed to augment these. Given the rapidly changing, complex, dynamic tasks faced by many military teams, a more fine-grained analysis technique is needed that can reflect moment-to-moment variations in performance. This is critical particularly to the development of feedback mechanisms, which must allow for delivery of timely, accurate performance information as tasks are being completed. Therefore, it is necessary to develop methods to measure behavioral latencies, behavioral probabilities, distribution of workload across members, task sequencing, and other aspects of team process. One way to accomplish this is to employ human performance modeling techniques [15]. In general, such techniques have the advantage of being able to describe complex, multi-operator tasks in a manner that is amenable to analysis. Further, they can provide a basis for measures of performance by specifying in detail what is to be considered effective team performance. A methodology that holds particular promise in this regard involves the use of Petri nets, a technique described in the following sections.

PETRI NET MODELS

Description of Petri Nets

Petri nets are the basis of a modeling technology that has been used to model a variety of phenomena [16] [17]. In general, Petri nets specify the relationship between two types of entities, places (or states) and transitions (events). Graphically, places and transitions are represented as circles and rectangles, respectively, and are connected by directed arcs. Formally, the structure of a Petri net is a bipartite directed graph, G = [P, T, A] where P = {p1, p2, ..., pn} is a set of finite places, T = {t1, t2, ..., tm} is a set of finite transitions, and A = {PxT}U{TxP} is a set of directed arcs. The set of input places of a transition (t) is given by $I(t) = \{p \mid (p,t) \in A\}$, and the set of output places of transition (t) is given by $O(t) = \{p \mid (t,p) \in A\}$. Sometimes the net will be defined as a function of the four entities: places (P), transitions (T), input functions (I), and output functions (O), where N = [P, T, I, O]. The two representations are equivalent.

Information, data, or conditions are represented as tokens in a Petri net. Tokens reside in places and move from one place to another through the firing of the transitions which are connected to the places by directed arcs. Figure 1 is a Petri net with a token in place 1. Places 2, 3 and 4 are called "empty places" because they contain no tokens. The marking of a Petri net is the assignment of tokens to places in the net, M:P->I, where I is an integer vector representing the number of tokens (M) assigned to each place (p_i). A marked Petri net, then, is identified as: N = (T, P, A, M).

The marking of Petri nets is important because it controls the firing of the transitions in the net. That is, the configuration of tokens in various places determines which transitions will fire. When a transition fires, it removes the token from the input place and passes it to the output place. Once a transition fires the net has a new marking.

There are often constraints or conditions on the firing order of transitions. For example, if a transition is not enabled, it cannot fire (this could occur if either the place contains an insufficient number of tokens or if other firing conditions of the transitions are not satisfied). A second constraint is that a transition cannot fire and pass a token when one is not present. A third constraint is that the firing of a transition will always result in the places of a Petri net containing a number of tokens greater than or equal to zero.

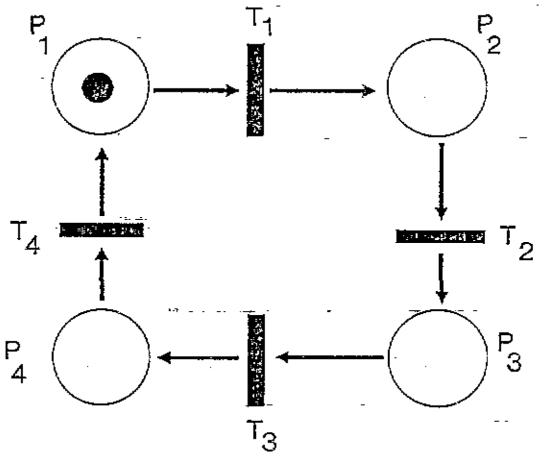

Figure 1. A cyclic Petri net.

The Meaning of a Petri Net

A Petri net is merely an abstract model, and as such, is not very useful until meaning is attached to its places, transitions, and tokens. Consider again the net in Figure 1. As it stands, the net could represent any cyclic process. In one example, the places p1-p4 might be labeled spring, summer, fall and winter, respectively, while transitions would represent climactic conditions which cause the change from one season to another. In other words, transition t1 would represent those conditions which lead from spring to summer. When these conditions are met, transition t1 would fire, and the token in p1 would move to p2.

A second example could have the net in Figure 1 representing a four member team. Places p1-p4 would represent the four individuals of the team, the arcs represent a channel of communication between members, the token represent a piece of information, and the transitions represent the act of communication (including possible modification of the message) between members. Since there are few constraints on the form of a net, this methodology will allow the modeling of any size team, highly complex tasks, and an unlimited number of connections between members. In addition, the processes represented in the net are also unlimited. For example, rather than verbal communication channels, the arcs in Figure 1 might represent electronically transmitted messages.

Advantages of Petri Nets for Modeling Teams

As a modeling tool for teams, Petri nets have several attractive properties. The first is their ability to model two critical aspects of team performance, concurrency and conflict. Concurrency occurs when different team members perform individual tasks independently and at the same time, which is the case with most military tactical teams. Conflict occurs when more than one team member requires a shared resource, or when the activity of one team member interferes with the activities of another. Consider the net in Figure 2. This net represents two individuals each performing three different tasks, represented as places p1, p2, and p3 for individual A and places p4, p5 and p6 for individual B. When individual A and individual B each complete their first two tasks (so that tokens are deposited in p3 and p6), t5 fires and the information is passed to individual C. Concurrency is represented, in general, by the individuals working alone at different places in a net when they are not dependent on each other. Conflict can occur in this net through the sharing of a resource. Here, if transition t1 fires, the token is removed from p7 and transition t3 is disabled until a token is deposited back in p7 by the firing of t2. In other words, the two team members cannot simultaneously complete their tasks since they each require a shared resource.

The second desirable property is that Petri nets are useful for modeling at various levels of abstraction. The net in Figure 2 represents part of a three member team interaction; as such, it is at the team level of abstraction. It is also possible to construct a net to represent each individual (in this case the net could represent the individual's

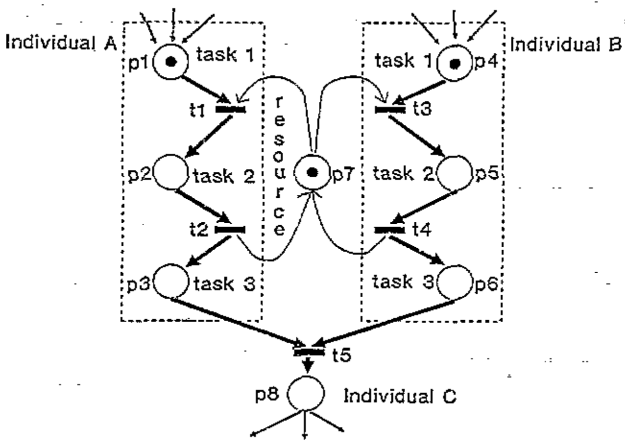

Figure 2. A two member team.

decision-making process), so that the individual would be the unit of analysis. It is also possible to construct a high level net representing an entire organization. Places in such a net could represent, for example, functional departments. Furthermore, the arcs in a Petri net could easily represent serial and/or parallel interactions among members, subteams, or teams. Once linkages are established, one can examine the influence of constraints at various levels of abstractions (e.g., individual, subteam, team, department or organization).

The third desirable property of Petri nets is that models may be analyzed in a variety of ways to validate a theoretical model of team performance and gain insight into the behavior of the system. They allow a rigorous examination of how teams behave in pursuit of task accomplishment. They can be verified via comparison of different team nets to one another, and validated via comparison of various net configurations with external indices of performance, such as outcome measures or expert ratings of performance. A popular method to verify the accuracy of a Petri net is through the construction of an incidence matrix. An incidence matrix defines net invariants such as constraints on the firing of transitions, and is useful as a means to verify the accuracy of nets. For example, it would be possible to identify from the net in Figure 2 the set of mutually exclusive places where the shared resource has the status of "in-use" or "not-in-use", but not both.

Reachability trees are a second major analysis technique for Petri nets. This approach is useful for identifying conflicts and blockages in the net. Specifically, it is possible to construct and analyze a tree (based on the paths defined by places and transitions) to ensure that all branches of the tree reach a desired state [18]. The tree is constructed by beginning with the initial markings of the net and generating all reachable states from the firing of the transitions.

Applications of Petri Nets to Modeling Team Performance

Over the past few years, Levis and his associates [19] [20] [16] [21] [22] [23] have employed Petri nets to study the organizational structure of decision-making. An individual's decision-making process is considered a two-stage model consisting of situation assessment and response selection. Constraints placed on the net follow the performance of an individual with bounded rationality. Individuals are linked together into a team and various constraints are placed on the nets to model alternative decision strategies, workload, and organizational structures. Their approach has been successfully employed to model submarine emergency decision-making.

Petri nets can also be employed to study team performance in a manner that is somewhat different from that of Levis and associates. Specifically, sequential (or functional) task nets can first be constructed to answer a variety of questions about team performance. A functional task net describes in a step-bystep fashion how the task is executed, including the interaction among team members. For example, a Petri net representation of the Replenishment at Sea simulation has been constructed [24]. This task is a three member team task designed to simulate the transferring of supplies from one ship to another while at sea. The functional net represents a top down decomposition of the task and is represented as 76 places and 93 transitions. It should be noted that this representation highlights the fact that even seemingly simple team tasks actually require a fairly complicated pattern of interaction among members. Alternative representations of the task based on a top down decomposition by individual has also been performed [25]. But the most effective and parsimonious representation can be obtained by performing a top down decomposition by function <u>within</u> each individual, see Figure 3.

Once the functional net is constructed, other nets representing such things as communication patterns, individual decision-making, and resource transfer can be "layered" on top of the functional net. That is, using the functional net as a foundation, other nets can be developed that describe only selected aspects of team performance. These nets are linked to the functional net because they are all based on a common task structure, but they are simpler than the functional net since they represent only a subset of tasks. For example, a verbal communication net

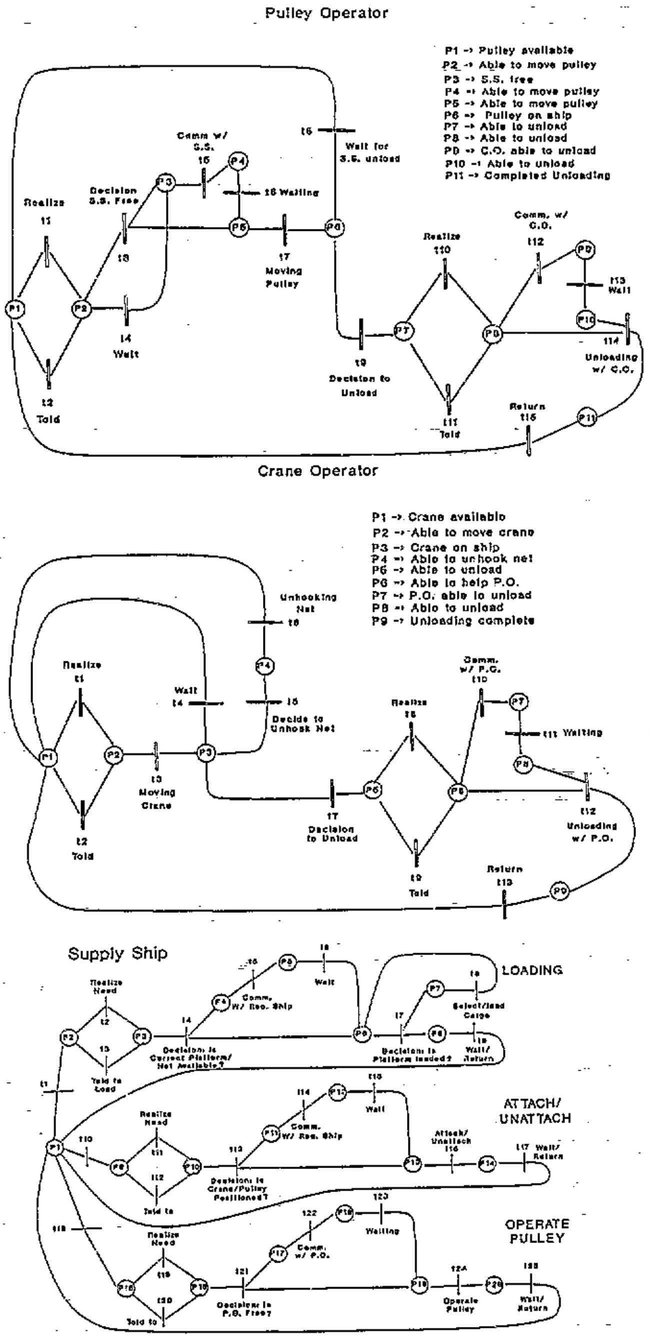

Figure 3. Replenishment at Sea, three team members.

could be devised that represents only the verbal communication among team members. These specialized nets allow a focused analysis of various aspects of team performance. In addition, the functional net itself can be studied to observe how it changes as a function of such variables as team member experience, workload, time pressure and other types of stress.

Implications for Training Design and Measurement

There are several ways in which Petri net methodology can benefit research into team performance and training. First of all, because Petri nets are a generic graphical representation tool, theories about team performance can be easily expressed, analyzed and communicated using this technique. It can be hypothesized, for example, that successful teams will tend to spend more time in certain sub-nets of a task than do less successful team. Additionally, as team members spend more time together, the evolution of their performance is easily modeled by the net. For example, it is reasonable to predict that the probabilities associated with certain transitions firing will be very different for mature versus immature teams. Once specified, hypotheses such as these can be tested to verify theoretical contentions by comparing the performance of teams in various parts of the net.

Second, with respect to developing team-based performance measures, Petri nets hold considerable promise. They are useful as a means to capture and document the moment-to-moment interactions characteristic of complex, multi-operator tasks. As such, they can be used to specify process measures of team performance. For example, when "effective" performance nets are identified these can be used to provide a basis of comparison for other teams. When teams behave differently than the comparison net, it can be determined whether these alternative strategies are appropriate; or if corrective performance feedback is required. In this way, a fine-grained analysis of team performance is possible, along with an indication of successful performance strategies.

Related to this, Petri nets are useful as a means to devise diagnostic and feedback mechanisms. As an aid for instructors, Petri nets can specify in detail how a task should be executed in terms of the interaction and information exchange among members, task sequencing, workload distribution, and behavioral latencies. This provides instructors with diagnostic information that is critical to determine why poor performance has occurred and feedback information that will help team members improve future performance. A detailed net can inform an instructor, for example, when a team member should compensate for another member due to high workload in specific positions. Training system designers would also benefit from such information when specifying diagnostic and feedback systems.

Also related to performance measurement, but with different emphasis, Petri nets can help training system researchers establish criterion measures for use in empirical work. For example, the refinement and validation of a new training or simulation principle for teams requires that baseline performance can be documented reliably. By the same token, methods are needed to document post-training performance so that appropriate comparisons can be made. Since Petri nets allow team behavior to be specified in detail, they can describe pre- and post-training performance in a manner that will allow even subtle changes in performance to be detected. In addition, they are valuable as a means to demonstrate changes in team processes, thereby providing a multi-faceted performance criterion.

SUMMARY

The Petri net formalism offers a viable means to test and evaluate theories of team performance and team effectiveness. It can further serve theory development and testing via generation and assessment of alternative plausible hypotheses regarding team performance. Petri nets are also useful as a basis to develop process measures of team performance. They can provide a means to track and assess the moment-to-moment performance and system changes characteristic of complex, multioperator tasks. As such, they can be used to guide researchers in criterion development and provide a model to aid system designers in defining diagnostic and feedback mechanisms. Further research is needed to develop this application of Petri nets so that effective performance feedback and instructional strategies for teams can be devised. Such research is being conducted at present at the Naval Training Systems Center as part of a 6.2 program aimed at developing training and simulation principles for tactical decision-making under stress.

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