Proceedings of the 2003 Winter Simulation Conference
S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, eds.

THE USE OF RECURSIVE SIMULATION TO SUPPORT DECISIONMAKING

John B. Gilmer, Jr.
Frederick J. Sullivan

Wilkes University
P.O. Box 111
Wilkes-Barre, PA 18766, U.S.A.

ABSTRACT

Recursive simulation is the technique of having simulated decisionmakers themselves use simulation to inform decisionmaking. In past research, these recursive simulation runs have evaluated the possible outcomes given that a decision was made one way or the other, allowing a simulated commander to consider the consequences of the alternatives. However, this allows only a reactive benefit, since the issue must first be framed in terms of a decision to be made. This paper explores other possibilities. It raises issues of how to represent the information about the future from projections not tied to a specific decision. Also considered is how the explicit details of what is projected might be conveyed back to the current planning context in order to make possible proactive actions.

1 BACKGROUND

Recursive simulation is the use of a simulation within a simulation to inform decisions made by the simulated decisionmakers. An example of this has been demonstrated with a military simulation "eaglet." That simulation was intended to be a much simplified surrogate for the U.S. Army's "Eagle" simulation, that would be of manageable complexity for research projects. The "eaglet" simulation represents military units of nominally battalion resolution, and up to a division scope, with explicit representation of decisionmaking by the simulated brigade and division commanders. The operation plans of these decisionmakers have contingencies for different employments of the reserve. Figure 1 is a representation of the state of an "eaglet" simulation run, illustrating some of the simulation features. Note that "eaglet" permits many simulation states, or when considered over time, trajectories, to be processed simultaneously. This figure shows just one of perhaps thousands of possible simultaneous possible states. The figure shows path plans for those units that are moving, including alternate routes. Units 10, 16, and 4 are the Blue reserves for the two forward brigades and the division, respectively. Investigation of the techniques and benefits of the ability to simultaneously process multiple states and their trajectories, "multitrajectory simulation" was the original purpose of "eaglet." Recursive simulation is only one of the possible applications of this capability.

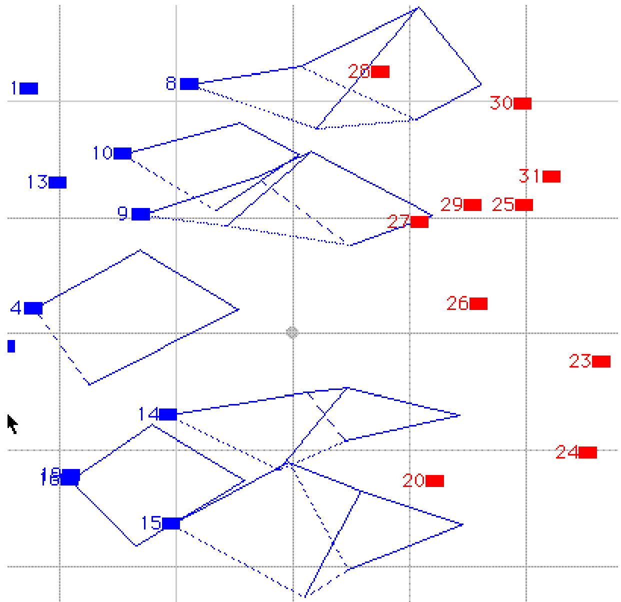

Figure 1: The "eaglet" Simulation

In past research, recursive simulation was used to project whether commitment of the reserve to support either of two subordinate attacking or defending forces would benefit the final state of the engagement, as evaluated by the decisionmaking entity. The recursive calls actually were part of a "decision study" within the simulation trajectory to support the decisionmaker's choice process. Each such decision study could be configured to include one deterministic replication for each possibility, or several stochastic runs for each possibility. The recursive runs started up with the current state of the simulation trajectory in which they were recursively called. It is possible, and was demonstrated, that the recursively called simulation runs could also in turn use recursion to support decisionmaking. The number of levels of recursion, the types and numbers of runs, and other parameters defining the "decision study" for different simulated commanders can be varied by setting parameters at the beginning of the overall simulation run as reported by Gilmer and Sullivan (2000).

The simulation used by simulated decisionmakers may be the same simulation, called recursively, as in the earlier research mentioned above. It may also be a different, perhaps simpler, simulation, as has been done in JWARS for the "commander's wargame" as reported by Argo et. al. (2002). In the latter case the simulation call is not technically recursive as a computer scientist might use the term, but many of the issues are similar. It is also possible to have the simulation within a simulation runs be created as asynchronous processes running in parallel with the main simulation, perhaps on other processors. This is a technical detail that fits within the general concept of recursive simulation as discussed in this paper.

The most obvious issue in the use of recursive simulation is computation expense. Each of the recursively called simulation runs is potentially almost as expensive as the original top level simulation run, so that the computational cost of the overall analytic study could easily be multiplied by a factor of hundreds or more. There are two answers to this issue. One is that computation is already very inexpensive, relative to other costs of using military simulation, and those costs will continue to decline. Recursive and multitrajectory simulation are techniques that attempt to capitalize on that diminishing cost. Computational power is harnessed in a useful way that was considered impractical when computation was expensive.

The second response is that the recursive runs can be scoped and limited to reduce their cost. For example, in some exercises of "eaglet" the first level recursion runs were stochastic with perhaps three replications for each possible choice, while the second level recursive runs were deterministic, and the choices at the bottom level were made without the use of recursive simulation at all. Another way to limit the cost is to use recursive simulation only for particular and important decisions, perhaps only those of the most senior commanders, and only for decisions where the issue is clearly in doubt. It is also possible to reduce resolution, reduce the scope of the units simulated in the recursive runs to those nearest the simulated commander's concern, and to limit the time frame of the recursive runs. Reducing the scope and changing resolution would require some modification or creation process for generating the initial states for the recursive runs that is less straightforward than simply using the current state of the active replication, but this challenge should be manageable. This has not yet been addressed with our research. It is not really within the intended scope of this paper since it addresses just an efficiency issue which will probably be at least mitigated by decreasing computation costs.

In applications of recursive simulation earlier by Gilmer and Sullivan (2000), the recursive runs were used to evaluate the benefit or lack of same for a decision being considered. The decision rule was whether to execute a particular contingency. Without recursive simulation, this rule would be resolved by evaluating a logical expression, perhaps testing for the existence of a dangerous state for the subordinate who the contingency would support. Another example that has not been exercised in "eaglet" yet might be a rule that recognizes an opportunity for which a contingency exists for the reserve to be committed in a way to reach an objective without having to encounter the enemy in strength. The recursive simulation runs would then be applied to those cases where, by the rule criteria, there is some doubt about whether the rule should "fire" (the contingency should be executed) or not.

2 THE PROBLEM

The important point from the background above is that, in order to invoke recursive simulation as described for decision support, the decision must already be framed, and some data to support its serious consideration exists. That is, the use of recursive simulation is not invoked unless some decision rule is being tested, and the rule evaluation results in something between an obvious "yes" and "no." The rule's criteria are necessarily in terms of the state of the simulation, or more properly, what the simulated commander knows about the state of the simulation. The use of recursive simulation can perhaps make this better, in that a simulated commander could occasionally use the technique to project future states of the battlefield. This would allow decision rules to have a temporal component, for example, the projected state of a particular subordinate at a particular time in the future. Even so, this can have severe limitations. This is perhaps best illustrated by an example, shown in Figure 2.

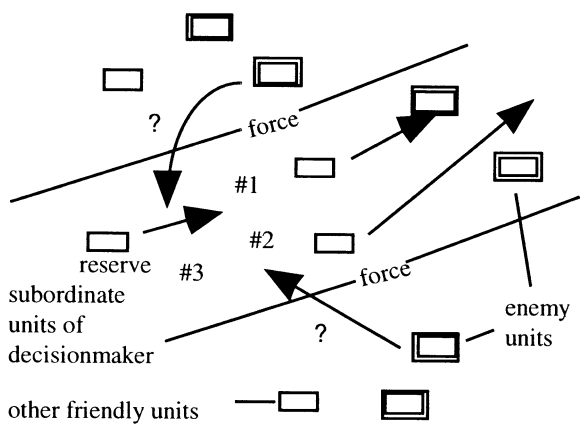

Figure 2: Example Context for Decisionmaking

Here a force is conducting an attack, which is expected to penetrate to the enemy rear forces. Two subordinate commands lead the attack, one follows in reserve. Contingencies (numbered #1, #2, and #3 in the figure) exist to commit the reserve to support either of the attacking subordinates, or to counter any enemy force that threatens from a flank. The flank threat would have a possibly catastrophic effect on the viability of the operation if not countered. Focusing on this last contingency, how would the decision rule be framed? There are several possibilities that can be grouped according to whether the decision criteria are referenced to a specific enemy unit.

1. The decision rule could be based on an aggregate measure of enemy force within a region defined as "flanks and rear." Figure 3 represents this, showing the organization of the plan and the defined "flank and rear" region within which the flank / rear threat would be evaluated. As part of the command cycle, the presence of enemy forces in this region would be assessed. This option does not implicitly provide the specific mechanism to task the reserve to do anything in particular. A rule of this sort does not actually fire until the threat has materialized. It is possible that with recursive simulation the rule could be referenced to future state, allowing it to fire early. But this is not as useful if the specifics of the threat, such as the identity and location of the enemy unit, are not explicitly recognized.

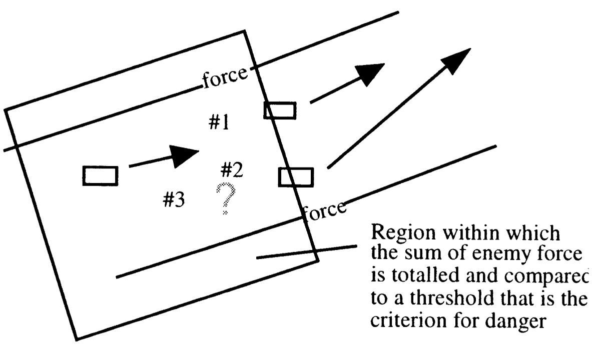

Figure 3: Aggregate Criterion for Danger to Flank / Rear

2. The decision rule could be based on filling a role in the plan for a "threatening enemy unit." Just as the plan includes roles, or slots, for the subordinate commands executing the operation, the plan could also include slots for specific enemy units recognized as fitting particular criteria, such as (in this case) an enemy unit threatening the rear of the force. Figure 4 illustrates this possibility.

This differs from evaluation based on aggregate measures in that the rule is for identifying that a particular enemy force is the danger. An advantage of this is that the tasking of the reserve can be oriented on the newly filled role of the enemy force, for example, to attack it or block its observed movement. However, if this is based on present state, it is very possible that the particular enemy force will not be recognized as a threat in time. That is, when the enemy force is recognized as meeting the criteria for filling this role, its threat may already be of critical or even catastrophic significance. This option is better than #1, but is still strictly reactive. If recursive simulation is used, a future threat could be recognized, but how would that be related back to the representation of the situation in the present?

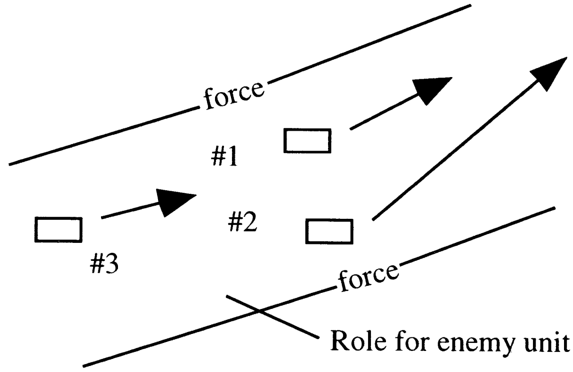

Figure 4: Role Filling Criterion for Evaluating Danger to Flank / Rear

The essence of the problem is that we need to have a specific rule that is being tested in order to make a decision. If the decision mechanism requires these rules to be very explicit and particular, this limits the decisionmaking to criteria. The rules must be defined in terms of objects such as subordinates and particular regions that are defined as part of the operation plan that is being executed by the simulated decisionmaker. However, it is not possible to make decisions for which the decision has not already been framed and a response formulated. Here is one place where human and simulated capabilities diverge dramatically. The human ability to improvise beyond formally defined decisions and criteria allows much more generally conceived contingency criteria and responses. The challenge of interest is to try to close that gap somewhat.

3 USE OF RECURSIVE SIMULATION FOR GENERAL PROJECTION

The use of recursive simulation earlier occurred on a need-defined basis. When a decision needed to be made, the two (or more) possibilities were explored with simulated projections. Each trajectory end state was evaluated according to a Measure of Effectiveness (MOE) defined as a criterion for informing the decision. (In the "eaglet" the MOE's used were losses and / or loss exchange ratio.) This MOE information was the only data returned from the recursive simulation runs, and even that was thrown away once the decision was made. This has the enormous advantage of simplicity.

As an alternative, or perhaps in addition, recursive simulation runs could be made, perhaps periodically, in order to provide information on future state. The idea is that, instead of decision rules being framed in terms of just present state, and possibly results versus MOE's for recursive simulation runs, a representation of future states is maintained. This allows recursive simulation runs to serve multiple decisions. The decisions can now be framed in terms of future state rather than just present state. MOE's about the possible future state for at least the baseline case can be harvested from the representation of the future rather than requiring, in each instance, fresh replications.

However, now we need some structure for representing what is believed to be the future (as projected by the recursive simulation run or runs). Furthermore, since the future is uncertain, there should be a representation of a variety of possibilities, if possible identified by probability if a rationale can be developed for such an assignment, and perhaps by a ranking of priority according to some other criteria such as seriousness. Figure 5 illustrates in a notional manner a representation of such a tree of possible future states. When a decision rule is evaluated, then, with reference to the future state, it might be in a form such as "If subordinate #1 is (projected to be) fully effective at time t2 with a probability of 85% or more, Then....."

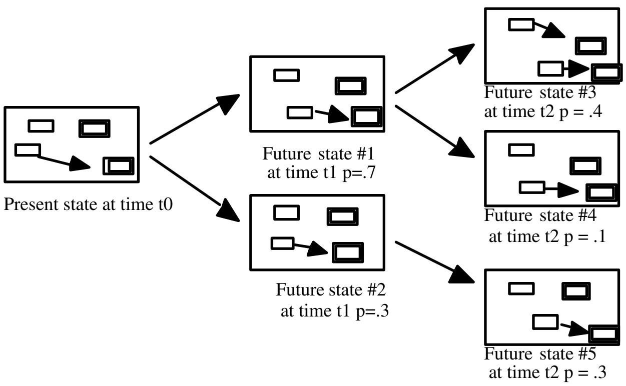

Figure 5: A Representation of Possible Future States

Conceivably, this means carrying the collection of all possible future states at a series of future times. This would likely present an unmanageable burden. Even though memory cost is coming down, it seems to be coming down more slowly than computation. If the future times to which decision rules refer are known, and are relatively small in number, then states for just those times could be retained. It is also possible to maintain a sparse collection of future states, and project with simulation as needed from the previous states kept to a time for which state information is needed on demand. If intelligence or other information is received that might change the perception of the future, the future state tree would either need to be modified. If the intelligence confirms or denies a state branch criterion, this is a matter of pruning. The whole state tree might have to be regenerated if the intelligence does not fit into the context of events anticipated, e.g. there is a surprise.

An alternative is to harvest from the states of the recursive simulation runs, perhaps as they execute, only selected information. For example, suppose one of the current decision rules under consideration is in the form mentioned above, where the effectiveness state of subordinate 1 is a criterion. Then one might simply maintain a tree of data about the respective states, which would be much more compact. Figure 6 illustrates this alternative. One could go even further and average the results at each time to give expected values, if that was sufficient for decisionmaking needs. The problem is that if the decision rules being tested change, or if some of the times are relative to present time rather than being at an absolute time, then the data may no longer be relevant, and a fresh set of replications is needed anyway to satisfy the needs for decision rule evaluation.

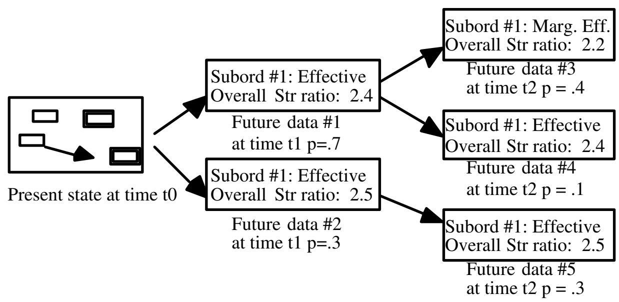

Figure 6: Data Structure Derived from Future States

A limitation of this method is that the information maintained about the future has very little specificity that can be used to structure particular responses. In this respect it is similar in its limitations to aggregated metrics applied to the current situation. Even so, this does provide an ability to support a limited form of decision rules that are sensitive to future conditions. One does not have to structure the rules entirely in terms of present observables.

The use of recursive simulation to generate projections outside the context of particular decisions requires a structure to maintain the information developed. This structure may be quite complex, and could become difficult and expensive to maintain. Simplified versions lack the specifics needed to support planning responses, but still allow decision rules to refer to the future.

4 ROLE ORIENTED DECISION SUPPORT

If the decisionmaking context includes specific roles for enemy and perhaps non-subordinate friendly forces, another possible mechanism becomes available. Consider the situation as portrayed in Figure 2 earlier. None of the enemy units present currently meets the criteria for being identified as a threat to the flanks and rear. (If the criteria were broad enough to allow these particular units to fill that role, then they probably would be so broad that most enemy units would also be able to fill the role, and that would not be useful.) Recursive simulation would used, likely with many trajectories, to evaluate the "threat to flanks and rear" possibility. The simulation mechanism would ensure that enemy units that would be otherwise engaged, perhaps by nearby friendly forces, would seldom meet the criteria for the enemy flank/ rear danger role. They would not reach those positions that would trigger that identification, because of interactions (that are represented as part of the simulation process) that would be extremely difficult to express or anticipate in the form of a rule. But those enemy forces that might threaten the flanks and rear because of difficult to anticipate opportunities, would fill the more closely defined role at a future time in some trajectories. Figure 7 shows such a situation, where an enemy unit is found that fills the "flank or rear threat" sometime in the future.

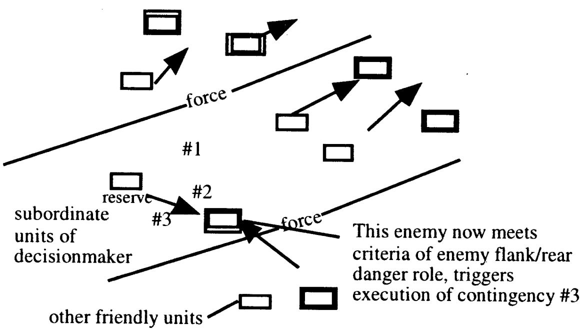

Figure 7: Recognition of Enemy Unit Role in a Recursive Projection

In the recursive trajectory, this recognition of the threatening enemy unit is reactive. But suppose the trajectory is considered as having a significantly high probability, or there are several such cases where this particular threat matures. Then in the present (the time from which the recursive runs begin) recognition of this specific unit as a significant potential future threat can be used to allow proactive decisionmaking. In particular, we would like for the simulated commander foreseeing this threat to take or consider a number of specific actions to prevent or mitigate the threat.

Once a role in the present is filled by a particular enemy unit believed to be a threat, a whole host of possibilities become practical for responses. There may be explicit contingencies in the force commander's operation plan. There may be implicit mechanisms that are built into the representation of the commander's staff, such as the tasking of intelligence assets, requests for combat support such as air support and counter mobility measures, and such. It may be that only certain of these responses are triggered until an evaluation of the "risk," in terms of a product of probability and importance perhaps, reaches a particular threshold. The identification of a threat unit and a sufficiently high risk might also initiate passing the identification to a superior commander or another supporting organization. The operation plan itself might be modified by the addition of roles for, perhaps, a "task force" which would be issued a fragmentary order to deal with the threat, using a mechanism of "Circumstance Descriptors" which has been explored with "eaglet." That mechanism allows for the modification of the role structure of a plan in response to circumstance particulars which are too numerous and specific to be practically implemented in a plan as preplanned contingencies Gilmer (2000). The crucial aspect to all of these responses is the identification of the future threat with a particular enemy unit in the present.

The identification of the threat from the future (projected) filled role needs to be conveyed to a present filled role. This is nontrivial. Figure 8 illustrates the present and future role structures of the currently executing plan of the force under consideration.

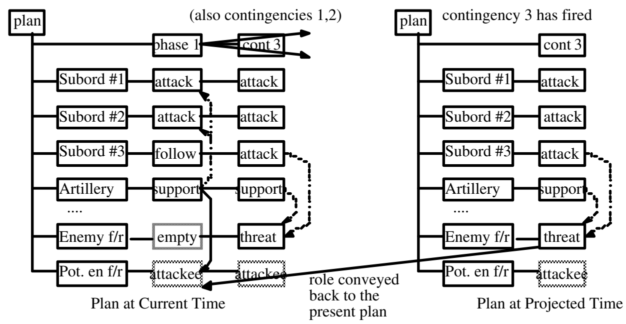

Figure 8: Present Plan Structure Modified to Include the Projected Future Threat

Here we see that the artillery role is automatically tasked against an enemy unit that fills the future threat role, which is filled by a unit projected to be a flank / rear threat in the future. Complicating this is the fact that there may be several future projected states in which the flank / rear threat contingency has fired. It is necessary to have a process that will collect the identifications of the enemy units as they exist (or are known about) in the present. Thus, there may well be a list of several enemy units filling multiple instances of the "Potential Enemy flank/rear Threat" role, and these will need to be placed in a priority order, perhaps by probability or a risk metric, for servicing by organic or directly supporting artillery or whatever various resources are at the decisionmaker's disposal. This, in turn, requires mechanisms to associate tasking for support to filled enemy roles.

Note that the existing role in the present operation plan for a threatening enemy unit, rather than a general structure of future states, now becomes the repository for the critical information about the future. It is not lost when or if future state data is thrown away. Once this role is instantiated by the mechanism shown, there is no need to retain further information from the projection, other than perhaps to gather aggregated or targeted statistics as described in the previous section. This mechanism conveys information specific enough for targeting: the identification of the specific enemy unit in the present. This allows the simulated decisionmaker the opportunity to act to mitigate the threat before it matures.

5 CONCLUSION

A trend that has been sustained now for decades is a rapid multiplication of computation power. There does not appear to be an impending end to this trend. The challenge before us is to take maximum advantage of this trend. One should ask, "How might this problem be solved if computation were free?" or "What problem, that seems hard, might be more easily solved if computation is free?" Recursive and multitrajectory simulation is an attempt to respond to this question in the context of military simulation, in particular to improve the representation of command decisionmaking. The simplest, most obvious (and expensive) approach has been demonstrated. But in that form it is limited, in particular to a reactive mode based on the way rules are structured in response to the current situation. However, computation is not completely free, and it remains a challenge how to best utilize this technique. This paper has outlined general approaches that allow recursive simulation to be used to allow decision rules to reference the future, and to bring specifics of future projections back to the present in a form to support proactive rather than just reactive action.

ACKNOWLEDGMENTS

This paper has further developed concepts from work supported by the U.S. Army Research Office under Grants DAAH04-95-1-0350, DAAG55-97-1-0360, and DAAG55-98-1-0451 with the sponsorship of the US Army Center for Army Analysis, particularly Mr. Gerry Cooper, Dr. Andrew Loerch, and Dr. Robert Alexander. The authors are indebted to these persons, as well as Chuck Burdick and Kosmo Tatalias, for their encouragement and support.

REFERENCES

Argo , H., J. Huynh, D. MacQueen, M. Grell, H. R. Blacksten, P. Bross, J. Prince, and C. Burdick. 2002. Plan Building in JWARS. 421-430. *Proceedings, 11th Conference on Computer Generated Forces and Behavioral Representation*.

Gilmer, J. 2000. Circumstance Descriptors: A Method for Generating Plan Modifications and Fragmentary Orders. *Proceedings of the 2000 Winter Simulation Conference*, ed. J. A. Joines, R. R. Barton, K. Kang and P. A. Fishwick. 303-311. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

Gilmer, J. B., and F. J. Sullivan. 2000. Recursive Simulation to Aid Models of Decisionmaking. *Proceedings of the 2000 Winter Simulation Conference*, ed. J. A. Joines, R. R. Barton, K. Kang and P. A. Fishwick. 958-963. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

AUTHOR BIOGRAPHIES

JOHN B. GILMER JR. worked in the development of combat simulations, with a focus on C2 representation and parallelism, at BDM, Inc. He was the chief designer of the CORBAN combat simulation. He has a Ph.D. in EE from VPI and currently teaches Electrical and Computer Engineering at Wilkes University. His e-mail address is <jgilmer@wilkes.edu>.

FREDERICK J. SULLIVAN is Dean of Technology and teaches Computer Science at Wilkes University, and earlier taught at Rose-Hulman and SUNY Binghamton. His expertise is in operating systems and object oriented software. His Ph.D. is in Mathematics, from LSU. His e-mail address is <sullivan@wilkes.edu>.