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13. ABSTRACT (Maximum 200 Words) In this work, we have explored the joint issues of 1) how to characterize flexibility for use in quantifying the value of decision alternatives, and 2) whether decision making methodologies incorporating parameters relevant to flexibility can be applied effectively in practical decision-making contexts. We have studied these issues in the context of complex multi-criteria planning tasks including military course of action planning, asset allocation and aviation scheduling. We have found that while providing some flexibility provides better performance, providing more flexibility (3 plus options) is not necessarily better than a little flexibility (2 to 3 options). Additionally, the configuration of assets can have a large impact on their cost and performance. These findings have significance for how the military can achieve high performance in courses of actions and in logistical support at relatively low cost.					
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Final Report

Quantifying Flexibility in Sequential Decision Making: Helping Commanders Assess Flexibility in Planning

January 1, 2003 – January 1, 2006

Caroline Hayes and Saif Benjaafar

Objectives:

- Formalize the notion of flexibility,
- Provide a framework for its modeling, measurement and evaluation,
- Study the relationship between flexibility and value,
- Explore application of these concepts in the task of selection of a course of action.

Planned outcomes:

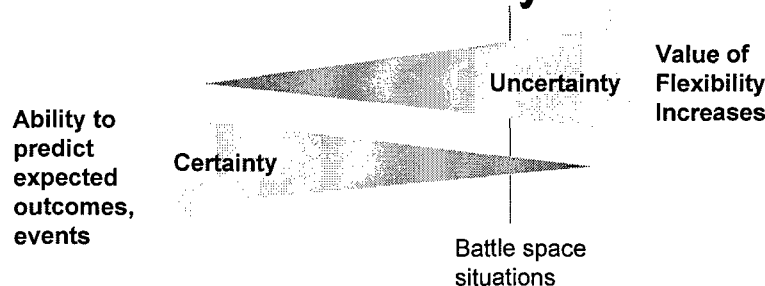
- A definition of flexibility and its measurement,
- An understanding of relationships between flexibility and value,
- A decision criterion for capturing flexibility,
- A basis for designing software tools to assist commanders in assessing the flexibility of action choices, and the value of flexibility in light of the current situation.
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In this work, we have explored the joint issues of 1) how to characterize flexibility for use in quantifying the value of decision alternatives, and 2) whether decision making methodologies incorporating parameters relevant to flexibility can be applied effectively in practical decision-making contexts. We have studied these issues in the context of complex multi-criteria planning tasks including military course of action planning, asset allocation and aviation scheduling.

Battle, whether open warfare or terrorist insurgency, can be characterized by rapid and unexpected changes, and much uncertain or unknown information (also known as the fog of war). Consequently, flexibility is a very important property in the courses of action (COAs) employed in meeting military and political objectives. Flexibility is especially valuable in highly uncertain situations in which the ability to react to unforeseen events may be more critical than the ability to identify the most effective plan for any given situation. In a battle situation, flexibility allows you to compensate for the fact that you do not know exactly what the enemy will do; flexibility allows you to succeed despite the unknown.

Motivations:

The Need for Flexibility in Plans



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Unfortunately, even skilled COA planners have difficulty assessing the relative flexibility of alternative COAs, and relevant mathematical measures of flexibility which they might use to assist them in these judgments have not been developed. The goals of this work are to study flexibility and its value in situations where knowledge is inexact, incomplete and the situation is rapidly changing, and to assess whether these methods can be translated into practical decision making contexts.

Personnel supported in full or part by this grant include faculty members Caroline Hayes and Saif Benjaafar; and graduate students Maher Lahmar (PhD), Dileepan Narayanan (masters), Yimin Yu (PhD, still in progress), Setareh Mardan (PhD), and Lakshmi Venkatesan (masters) and The results of this work are reported in 5 theses [1 - 5] and 12 refereed articles [12, 15 – 18, 21 - 27] (see full references below under the headings “Masters and PhD Theses” and “Publications”). These publications can be obtained either through the journal or conference proceedings in which these articles have appeared, or by sending a request to the relevant authors.

Approach. This work was carried out using a combination of theoretical and empirical approaches. We used a theoretical approach to develop the basic concepts of flexibility, and empirical approaches including simulation, and empirical testing with human subjects to determine the practical impact of the concepts and models developed in this work.

In this work we explored:

- A framework for thinking about plan flexibility in adversarial situations,
- An experiment assessing how decision support tools that help explore flexibility impact human plan quality
- Flexible asset configurations that maximize performance while minimizing training and procurement costs.

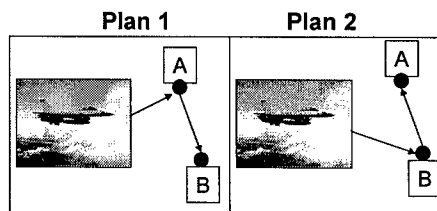
Flexibility Framework. There are many ways in which one might define flexibility. To define flexibility in the context of a plan, it is first necessary to establish a definition for a plan. In this work, *a plan* is: A commitment of *assets to tasks* or *roles* which forward mission objectives. Thus, a COA fits this definition of a plan when it is specified as a configuration of assets (units and equipment) at starting positions in the battlespace. Each unit is typically given a specific role or mission which is intended to carry out some aspect of the commander’s intent. Flexibility in a plan can be defined in several ways:

1. Alternate *future sequences* for tasks
2. Alternate *future* assignments of *assets* to *tasks*.

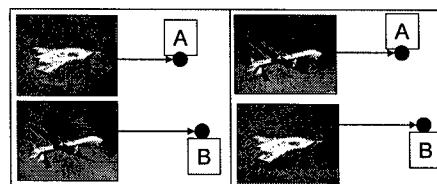
We have adopted definition 2. for the purposes of this work.

Flexibility in a Plan is:

- Alternate *future sequences* for tasks



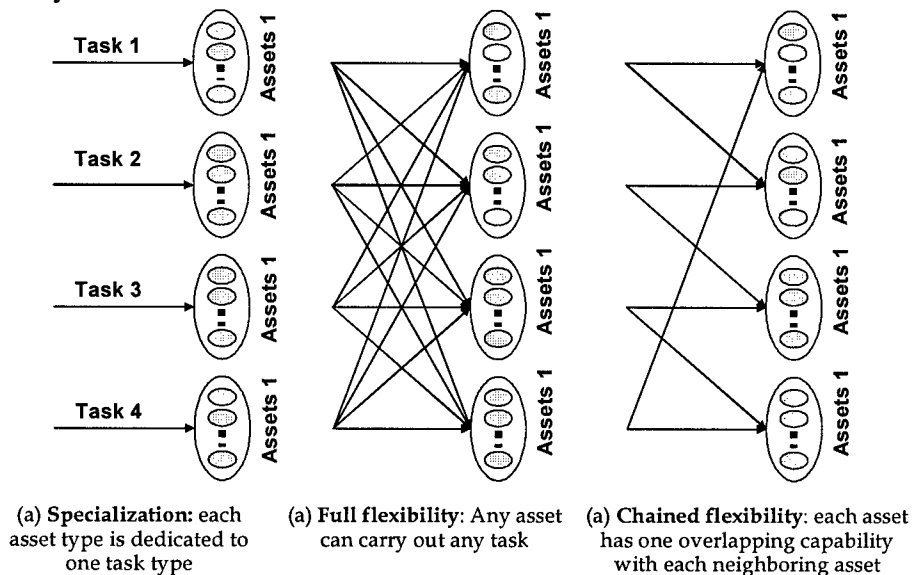
- Alternate *future assignments* of *assets* to *tasks*.



Major findings.

The value of flexibility:

1. **Flexibility results in superior average performance.** Introducing some flexibility can have a significant impact on performance; two or three options leads to much better performance than only one. This is particularly true in highly variable or environments or environment where assets are subject to high workload (such as battle situations).
2. **Lots of flexibility is not significantly better than a little flexibility.** The impact of flexibility on performance exhibits strong diminishing returns, with most of the benefit realized with relatively limited flexibility. In other terms, large numbers of options do not necessarily offer much advantage over a few good options.
3. **There are specific ways of offering flexibility that are more advantageous than others.** A "chaining" configuration of flexibility can be nearly as effective as a full flexibility configuration. A chaining configuration is shown in the Figure, below. In a chained configuration, each asset should be capable of performing/being used for at least two types of tasks as shown. Such a configuration provides high performance and relatively low cost.



The impact of flexibility on decision making:

4. **The performance of intermediate-level COA planners (1 - 5 years experience) was significantly improved** when they used a computer decision support tool to help them consider a wider range (i.e. more flexible) of options. However, the performance of expert-level COA planners (6 plus years of experience) was not significantly improved when they used the same tool.
5. **Subjects produced significantly better Effects-Based Operations Plans when they were given both plan quality assessments, and information about remaining resources** (allowing them to assess flexibility in terms of unallocated assets remaining)

Discussion

The findings above tell us several things about current practice in military planning and asset assignment, and about what future practice should be. Finding 1 above confirms the appropriateness of the existing practice of exploring several appropriate courses of action for any given situation. It is always recommended the planners find several COA; in practice, they often explore between 1 and 3 options, often not more. Finding 2 might suggest that exploring more than 3 options (more flexibility) is not necessarily better than exploring just a few options. Thus, while commanders frequently express concerns that the 2 to 3 options that their subordinates tend

to produce may not be enough, the Finding 2 suggests that perhaps there may not be such a great advantage/pay-off in taking the time to explore many COA options in depth.

Findings 1 and 2 provide some explanations and insights into Finding 4. There are two observations in Finding 4. First, that experts are not greatly helped by having more options generated for them. This is consistent with Finding 2. In fact, Finding 2, that more options does not offer significant benefits over a few (2 to 3) options, may explain why expert performance is not significantly improved when they are shown more COA options. However, the second observation, that intermediate-level planners' performance was improved by being shown more options, appears to contradict Finding 2. An examination of nature of the options generated by the intermediates provides some insights into what is happening. The options generated by the intermediates were not always very good ones, and some violated the rules for proper formation of COAs. This may indicate that if one is going to explore only a few options, they need to be high quality options. Thus, finding 2 may not hold if the options are not of sufficient quality, or are not sufficiently distinct from each other. Finding 4 may also indicate that intermediate COA planners are often capable of recognizing a high quality COA, even if they can't always generate many good ones.

Finding 3, on chained asset configurations, suggests that by teaching planners to recognize and use this type of asset assignment, they may be able to reduce training and equipment costs, while maintaining high flexibility and performance in battle.

Finding 5, suggests what types of information that decision makers need to have available, at a minimum in order to assess the flexibility of a given choice. Even if the decision makers could have derived this information by hand, in practice they did not. Having it made available by a computer tool was beneficial to them.

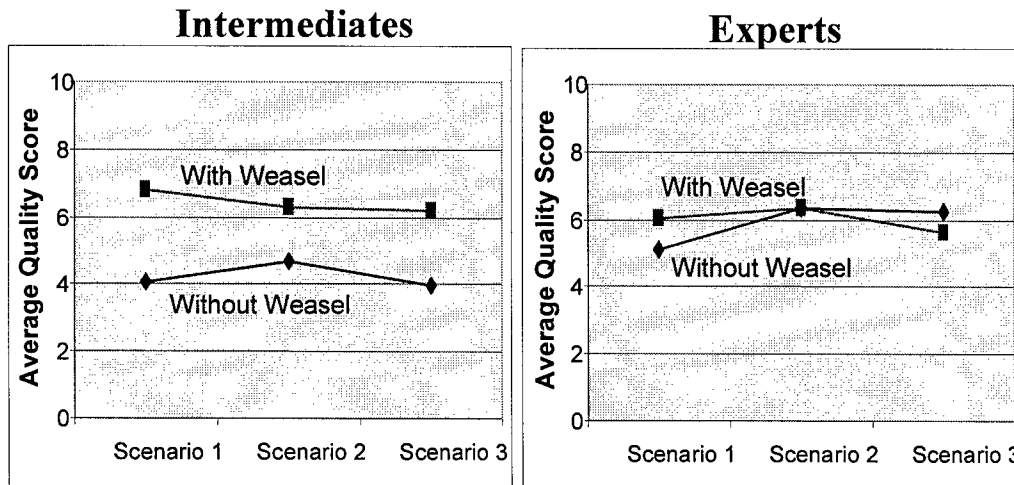
Conclusions

We have confirmed both theoretically and empirically that flexibility in asset allocation does lead to better performance, but that a little flexibility (2 to 3 options) provides almost the same benefits at much lower cost than much greater flexibility. Furthermore, that certain configurations of assets, in particular chained flexibility, offers high performance at less cost than many other configurations. Lastly, decision support tools can offer benefits to intermediate level planners and improve their performance in generating plans by helping them to identify higher quality options, and by providing appropriate information to help them assess the flexibility of different plan options.

Main Findings of Student Theses:

1. **Maher Lahmar** (2003) PhD Thesis, "*Scheduling and Facility Design with Flexibility*" placement: Assistant Professor at the University of Houston. This work studied the impact of resequencing flexibility on performance.

2. **Captain Adam Larson** (2004) Masters Thesis, "*The Impact of Computer Decision Support on Military Decision Making*." The performance of planners with an intermediate level of COA planning experience (1 to 5 years) was improved significantly when they used a decision support tool that would generate additional COA options for them (See figure below). However, the performance of expert COA planners (6 plus years of experience) was not significantly improved.



The goal of this work was to determine whether computer decision support tools have a measurable impact on the quality of the courses of action generated by military personnel. Larson conducted an experiment in which 18 subjects (military students and personnel) were given battle scenarios. They were asked to generate possible enemy courses of action consistent with the information in the scenario, and to select a small set of "best" COAs to pass on to their commander. Each subject solved one scenario by hand, and the other with the assistance of Weasel, a computer decision support tool which automatically generates a number of possible enemy courses of action consistent with specified intelligence information. Larson found that the performance of subjects with an intermediate level of experience (1 – 5 years experience in COA planning) was significantly improved ($p\text{-value} = 0.0002$), while the performance of experts (6 or more years of experience) was not significantly changed ($p\text{-value} = 0.251$).

3. **Dileepan Narayanan** (2006) Masters Thesis, "*Plan-Assist: An Effects-Based Operations Planning Tool*." The performance in creating effects-based operations plans was significantly improved when a decision support tool offered them feedback on both the quality of their plans, and the impact on resources (i.e. how much resources would be left in reserve). However, performance was not significantly improved (over no support) when offered either of these types of information alone.

4. **Setareh Mardan**, (2006) Ph.D. Thesis, "*Control Policies for Stochastic Production-Inventory Systems*," University of Minnesota. Studied asset flexibility described in Findings 1 and 2, above.

5. **Lakshmi Venkatesan**, (2006) Masters Thesis "*Modeling and Analysis of a New Flexibility Configuration, MS Thesis*," University of Minnesota. Studied chaining configurations described in finding 3, above.

Personnel Supported:

Faculty: Caroline Hayes and Saif Benjaafar, 1.25 months summer salary, each.

Graduate students: Dileepan Narayanan (masters), Maher Lahmar (PhD), Setareh Mardan (PhD),

Air Force Personnel associated with project (supported directly by Air Force):

Captain Adam Larson

Masters and PhD Theses (associated with project):

1. Maher Lahmar (2003) PhD Thesis: "*Planning and Scheduling in Dynamic Environment.*" Placement: Assistant Professor at the University of Houston.
2. Captain Adam Larson (2004) Masters Thesis: "*The Impact of Computer Decision Support on Military Decision Making.*"
3. Dileepan Narayanan (2006) Masters Thesis: "*Plan-Assist: An Effects-Based Operations Planning Tool.*"
4. Setareh Mardan, (2006) Ph.D. Thesis, "*Control Policies for Stochastic Production-Inventory Systems,*" University of Minnesota,
5. Lakshmi Venkatesan, (2006) Masters Thesis, "*Modeling and Analysis of a New Flexibility Configuration,*" University of Minnesota.

Publications: peer-reviewed publications submitted and/or accepted during the period of the award in chronological order. This includes both publications directly resulting from the funded work, and other relevant publications.

6. Hayes, C., A. Pande, and C. Miller, "Etiquette in Human Computer Interactions: What does it mean for a Computer to be Polite? or Who Needs Polite Computers Anyway?," in Proceedings of the *Workshop on Etiquette for Human-Computer Work*, held at the AAAI Fall Symposium (AAAI Press, California; North Falmouth, Massachusetts; November 15-17, 2002) Technical Report FS-02-02, pp. 47-51.
7. Qian, A. and C.C. Hayes, "Feature Conglomerator: Helping Users Identify Cost Effective Feature Interpretations," *Proceedings of the Design for Manufacturing Conference* held at the Design Engineering Technical Conferences and Computers and Information in Engineering Conference (Chicago, Illinois; September 2-6, 2003). Paper No. DETC2003/DFM-48133, [proceedings on CD-ROM]
8. C.C. Hayes and U. Ravinder, "Weasel: A User Guided Enemy Course of Action Generator," Conference on Knowledge-Based Intelligent Information and Engineering Systems (KES), Special Session on *C2 and Situation Awareness* (University of Oxford, United Kingdom; September 3-5, 2003), [proceedings on CD-ROM].
9. C.C. Hayes and U. Ravinder, "Weasel: An Automated Planner that Users Can Guide," *IEEE Systems, Man and Cybernetics* (Washington, D.C.; October 5-8, 2003) Paper No. HMS Special P1-5, [proceedings on CD-ROM].
10. C.C. Hayes and F. Akavi, "A Comparison of Two Multi-Criteria Decision Making Technologies," *IEEE Systems, Man and Cybernetics* (Washington, D.C.; October 5-8, 2003) Paper No. HMS Special P1-6, [proceedings on CD-ROM].
11. D.M. Gaines and C.C. Hayes, "Simultaneous Identification of Planning Sub-goals and Construction of Operator Instantiations for more Flexible Planning," *Journal of Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AIEDAM)*, special issue on New AI Paradigms for Manufacturing, November 2003.
12. Lahmar, M., H. Ergan and S. Benjaafar, "Resequencing and Feature Assignment," *IEEE Transactions on Robotics and Automation*, 19, 89-103, 2003 (M&SOM Best Paper Award, Honorable Mention).
13. J. Herrmann, J. Cooper, S. K. Gupta, C. C. Hayes, K. Ishii, D. Kazmer, P. A. Sandbourn, W. H. Wood, , "New Directions in Design for Manufacturing," Proceedings of the *Design for Manufacturing Conference* held at the Design Engineering Technical Conferences

(DETC'04), Salt Lake City, Utah, September 28 – October 2, 2004. [Proceedings on CD ROM].

14. Akhavi, F. and C. C. Hayes, A Comparison of Multi-Criteria Decision-making Techniques," poster at the 48th Annual Meeting of the Human Factors and Ergonomics Society, New Orleans, LA, September 20-24, 2004.
15. Gurumurthi, S. and S. Benjaafar, "Modeling and Analysis of Flexible Queueing Systems," *Naval Research Logistics*, 51, 755-782, 2004.
16. Benjaafar, S., M. Elhafsi and F. de Véricourt, "Demand Allocation in Multi-Product, Multi-Facility Make-to-Stock Systems," *Management Science*, 50, 1431-1448, 2004.
17. Hayes, C. C.; Capt. A. D. Larson and U. Ravinder "Weasel: A Mixed-Initiative System to Assist in Military Planning," International Conference on Automated Planning and Scheduling (ICAPS), June 5 – 10, 2005, Monterey, CA.
18. Larson, Capt. A. D. and C. C. Hayes, "An Assessment of Weasel: A Decision Support System to Assist in Military Planning," Human Factors Ergonomic Society (HFES) 49th Annual Meeting, September 26 – 30, 2005, Orlando, FL.
19. Hayes, C. C. and R. A. Anderson, "Differential Benefits Derived from Decision Support Tools for Domain Novices versus Experts," IEEE conference on Systems Man and Cybernetics (SMC), October 10 – 12, 2005, Hawaii, USA.
20. J. Corney, C. C. Hayes, V. Sundararajan, P. Wright, "The CAD/CAM Interface: A 25-Year Retrospective" American Society of Mechanical Engineers *Journal of Computing and Information Science in Engineering*, 5(3): 188-197, September, 2005.
21. Lahmar, M. and S. Benjaafar, "Design of Dynamic Distributed Layouts," IIE Transactions, 37, 303-318, 2005 (Outstanding Material Handling & Logistics Research Paper Award, CICMHE; Featured Article in IIE Solutions Magazine)
22. Benjaafar, S., William L. Cooper and J. S. Kim, "On the Benefits of Pooling in Production-Inventory Systems," *Management Science*, 51, 548-565, 2005 (M&SOM Best Paper Award, Honorable Mention).

Additional Publications: based in full or part on work resulting from the award, accepted or printed between January 2006 and August 2006.

23. Hayes, C. C. and R. Anderson, "Benefits of Decision Support Tools for Users with Differing Levels of Domain Expertise" *Proceedings of the Human Factors and Ergonomics Society 50th annual meeting*, San Francisco, CA., October 16-20, 2006, Proceedings on CD-ROM, Paper no. 503.
24. Larson, A. D. and C. C. Hayes, "An Assessment of a Decision Support System to Assist in Military Planning," *Behavior Representation in Modeling and Simulation (BRIMS) Conference*, Baltimore, MD, May 15-18, 2006.
25. Hayes, C. C., "Challenges in Designing Tools for Domain Experts" *Workshop on HCI & Information Design to Communicate Complex Information*, Memphis, TN, February 16-17, 2007.
26. Lahmar, M. and S. Benjaafar, "Sequencing with Limited Flexibility," accepted for publication in IIE Transactions.

27. Benjaafar, S., Y. Li and D. Xu, "Demand Allocation in Systems with Multiple Inventory Locations and Multiple Demand Sources," accepted in *Manufacturing and Service Operations Management*.

Honors or Awards received during the Grant Period. List lifetime achievement honors such as Nobel Prize, society fellowships, etc. prior to this effort.

Caroline Hayes

- Visiting researcher, National Aeronautics and Space Administration (NASA), Ames Research Center, Moffet Field, CA, February – May 2004.
- Visiting professor, Software Institute, Fudan University, Shanghai, China, May – June, 2004.
- Program Chair, American Society of Mechanical Engineers, the 7th *Design for Manufacturing Conference*, 2003.
- Conference Chair, American Society of Mechanical Engineers, the 8th *Design for Manufacturing Conference*, 2004.
- Program committee, panel chair; conference on “*Information, Technology, and Everyday Life*,” University of Minnesota, the President’s 21st Century Interdisciplinary Conference Series, 2005.
- Program committee, session chair; IEEE Systems Man and Cybernetics, 2005.

Saif Benjaafar

- Visiting Professor, Laboratoire Génie Industriel, Ecole Centrale Paris, Paris, France, 2003
- Visiting Professor of Industrial Engineering and Engineering Management, Hong Kong University of Science and Technology, 2004
- Chair, *NSF Symposium on Supply Chain Managements*, Minneapolis, Minnesota, May 6-7, 2004.
- Chair, NSF IUCRC Planning Conference, Minneapolis, MN October 23, 2003.
- Member, International Advisory Committee, The International Forum for Research, Teaching, and Practice of Operations and Supply Chain Management, Bali, Indonesia, December 15–17, 2005
- Member, International Program Committee, *The International Conference on Robotics and Automation*, New Orleans, Louisiana, April 26-May 1, 2004.
- Associate Editor for IEEE Transactions on Automation Science and Engineering
- Member, International Advisory Committee, The International Forum for Research, Teaching, and Practice of Operations and Supply Chain Management, Bali, Indonesia, December 15–17, 2005