# The Prioritization of Technologies in a Research Laboratory

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*Abstract*—This paper considers the prioritization of technologies at the Army Materials Technology Laboratory. The authors have worked with the management of the laboratory in identifying the criteria and the technologies to be evaluated. A mathematical model was developed to combine the subjective criteria with a single objective criterion. The three divisions of the laboratory and a technical working group of the Army Materiel Command provided the input data for the model. The criteria weights were determined by the Analytic Hierarchy Process through a hierarchical representation and pairwise comparisons. The results from the three divisions were aggregated to yield a prioritized list of technologies to be used by the management of the laboratory for funding decisions of projects within technology areas.

*Keywords*—Research management; technologies prioritization or ranking; materials technologies; U.S. Army Laboratory; programs evaluation; subjective and objective criteria; application.

## Introduction

One of the most challenging aspects of research and development (R&D) in a multitechnology government laboratory is the allocation of the available resources among competing research programs (technologies). Since the resources such as, funds, manpower and facilities are limited, critical decisions have to be made as to which technologies to pursue vigorously and which to deemphasize. A well-chosen R&D portfolio provides the means of gaining national stature and can protect budgets and personnel during periods of fiscal austerity.

The task of comparing many competing technologies for the purpose of evaluating or prioritizing them becomes very complex due to the many subjective criteria involved and the lack of information or uncertainty on the potential contributions of the technologies toward the criteria or objectives. The authors present in this paper a work performed for the Army Materials Technology Laboratory (MTL) regarding prioritization of the technologies in which the laboratory is conducting research.

MTL is located six miles from downtown Boston, MA. It employs approximately 600 personnel of which 270 are professionals and 70 are Ph.D.'s. The Laboratory consists of three divisions, i.e. the "Metals and Ceramics" division (MCL), the "Mechanics and Structural Integrity" division (M&SI) and the "Organic Materials" division (OML). It is known for its expertise in the field of materials research and is the Army's lead laboratory in structural integrity, corrosion prevention and control, materials and manufacturing testing technology, solid mechanics, lightweight armor, adhesive bonding and composites research. Its main mission is to function as lead laboratory in future Army systems and to provide direct support to systems program managers in the areas of production problems and failure analysis for fielded systems.

The management of MTL had recently become concerned regarding the future of the laboratory. With the expectation of continued lower funding, the agency endeavored to determine which areas of research would yield the most success and therefore visibility. MTL management sought to control its own destiny and consequently decided to use existing resources and expertise to determine what research the facility could do best.

The technologies evaluation project at MTL started in the summer of 1985. The authors worked closely with the management of MTL in identifying the appropriate criteria and in developing a mathematical model for the prioritization of technologies. During the next two years the model was applied using data supplied by the three divisions at MTL.

Hundreds of articles have been published on R&D project selection and resource allocation methods (see surveys in [1], [6], [7], [19], [20]). The developed models include normative ones, such as, cost-benefit analysis, Operations research models, implicit linear models, and descriptive ones, such as, policy capturing models [2]. The evaluation of technologies in a laboratory is a different task from the evaluation of projects. First, because different evaluation criteria have to be used, and second, since technologies are usually very much broader in scope as compared to project proposals, their evaluation is based on much more uncertain information. In addition, the technologies selected draw new R&D directions for a laboratory which will affect the content of future project proposals.

Very few cases of technologies evaluation in a laboratory setting have been reported in the literature. Dean and Roepcke [4] have developed a model for use in allocating resources to a multilaboratory, multitask research and exploratory program. Relative values of the objectives were obtained by subjective estimates using rank ordering and constant differences over a 3:1 scale. Krawiec [10] has evaluated technologies, referred to as program elements, in the Solar Thermal Research Program of the Department of Energy. He used a scoring method augmented by probabilistic risk assessment.

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In this paper, a rating approach is presented for prioritizing the technologies at MTL. Since more than one level of criteria had to be used, a hierarchical structure of criteria and technologies was developed. The various criteria were pairwise compared to derive relative priority weights using Saaty's Analytic Hierachy Process (AHP) [16], [17]. Two different types of criteria were identified, subjective and objective criteria. Qualitative ratings of the technologies were elicited against each subjective criterion. For the single objective criterion, "systems needs and military utility," ratings of the technologies were developed using quantitative data obtained by the Army systems authorities who are making use of the technologies. The qualitative and quantitative ratings were weighted by the criteria weights in a linear model to yield the technology measures. Although the prioritization model was developed specifically for MTL, the whole approach including selection of criteria and determination of weights and ratings is general and can be utilized with slight modifications to evaluate and rank technologies in other research laboratories. The paper is divided into two main sections, the model development and the application of the model.

## Model Development

The development of the technologies prioritization model was accomplished in three steps: 1) the criteria to be used to evaluate the technologies were identified and classified, 2) a general mathematical model was formulated to determine the technology measures, and 3) a methodology was developed for the determination of the various types of weights and ratings that are fed into the model to yield the technology measures.

### *Criteria Identification*

The technologies prioritization problem in a research laboratory is not a single criterion, but a multiple criteria problem. The identification of criteria involves the consideration of a variety of factors such as the mission of the laboratory, its image in moving to innovative research directions, and the availability of resources required to achieve success in its efforts. The identification of criteria was performed by a team consisting of the management of MTL and the authors. The management of MTL was represented by the associate director, the chief of the Program Planning Division, the director of the Office of Technology Forecasting and the R&D coordinator.

The team was presented initially with a list of 25 major technical areas (technologies), and a list of 11 criteria, both of which were compiled earlier by the Office of Technology Forecasting at MTL. The list of 25 was cut down to 22 technologies, shown in Table I, and was thought to be an accurate list representing all research programs undertaken by MTL. In order to check the validity of the 11 criteria list the following rules were used:

TABLE I
List of Technologies

| |
|---|
| 1. Joining |
| 2. Elastomers |
| 3. Metals |
| 4. Polymers |
| 5. Organics processing |
| 6. Composites processing |
| 7. Quality Assurance |
| 8. Design and engineering properties/methods |
| 9. Analytical and numerical methods |
| 10. Resin matrix composite |
| 11. Fibers |
| 12. Electronics/electro- optics |
| 13. Metal processing |
| 14. Mechanics of processing |
| 15. Ceramic processing |
| 16. Ceramics |
| 17. Automated process control |
| 18. Ceramic matrix composite |
| 19. Powder processing |
| 20. Metal matrix composite |
| 21. Surface treatment/coatings |
| 22. Macro composites |

1) Orthogonality of criteria [3]: The criteria used must be mutually exclusive (orthogonal) rather than being highly correlated or having a high degree of overlap. Highly overlapping or correlated criteria should be combined.
2) Completeness of the criteria list: All criteria relevant to the overall objective of the organization should be considered.
3) Reasonably small criteria list: The number of criteria should be reasonably small to allow consistent pairwise comparisons. Saaty [16], [17], whose AHP approach is used later in this paper to determine criteria weights, suggests a maximum number of seven. He was led to this number by Miller's psychological observation [12], that an individual cannot simultaneously compare more than seven objects (plus or minus two) without being confused.

In order to check agreement with the first rule, a correlation analysis was performed on technology ratings with respect to each criterion. The ratings were provided by several members representing the management of MTL. The idea was to reduce the number of criteria by merging overlapping or highly correlated criteria. A set of six criteria were merged into two new criteria. Regarding the second rule, two criteria were deleted because were thought to be irrelevant and one new was added. The third rule was satisfied automatically since the number of criteria was reduced to 5. The final set of criteria with the corresponding definitions, shown in the first two columns of Table II, was approved by the management of MTL.

### *Classification of Criteria*

Unfortunately, the contributions technologies make toward most of the above mentioned criteria, cannot be measured in quantitative terms. For example, it is very difficult to express quantitatively the relative contribution of each technology toward the "forward looking" criterion. On the other hand, the contribution a technology makes toward the "systems needs and military utility" criterion is more tangible and can be measured by the extent military systems benefit from the

TABLE II
DEFINITIONS OF CRITERIA AND INTENSITIES

| Criterion | Definition | Criteria Intensities Definitions |
|---|---|---|
| 1. Systems Needs and Military Utility (SN&MU) | A measure of the potential a technology has to solve serious systems problems; potential to be used in many systems; potential in achieving the objectives of the mission areas | (The objective criterion does not have criteria intensities) |
| 2. Unique Army Interest (UAI) | A measure of the Army's interest in a technology versus interest of other sources (other Department of Defense agencies, Industry, . . .) | 1. Army has an exclusive interest<br>2. Technology is not likely to be transferred from other sources<br>3. Technology is likely to be transferred from other sources<br>4. Technology can definitely be transferred from other sources |
| 3. Resources Availability (RA) | A measure of the availability of manpower, facilities and equipment | 1. Resources already exist inside MTL<br>2. Resources exist outside MTL but can be acquired within ceiling and funding limitations<br>3. Resources exist outside MTL but cannot be acquired within ceiling and funding limitations<br>4. Resources are not currently available inside or outside MTL |
| 4. Critical Materials (CM) | A measure of the reduction in the use of critical materials (development of critical materials substitutes) | 1. Significant reduction in use of critical materials<br>2. Moderate reduction in use of critical materials<br>3. No impact in use of critical materials<br>4. Increase in use of critical materials |
| 5. Forward Looking (FL) | A measure of the potential a technology has to attract and hold competent people and to raise the image of MTL as a result of it being at the frontier of science and engineering | 1. Outstanding<br>2. Above average<br>3. Average<br>4. Backward looking |

development of that technology. The criteria are classified in this study as subjective or objective on the basis of the means used in evaluating the contribution of each technology toward them, i.e., subjective judgment (qualitative) or objective data (quantitative), respectively.

All criteria except the "systems needs and military utility" criterion were classified as subjective. For the "systems needs and military utility" criterion, data were obtained outside the laboratory, from a Technical Working Group (TWG) of the Army Materiel Command (AMC). A TWG representative is selected from each agency under AMC, responsible for performing work in a particular research area. A TWG meets periodically to assess ongoing programs and evaluate future programs for the likelihood of success. Recommendations from this group will effect how funding will be divided, thereby allowing these research representatives and their agencies some budgetary influence.

The TWG, which met to assess the ongoing programs of MTL, identified 30 system problem areas and potential improvements within each one of these areas which can be contributed by each one of the technologies. The problem areas and the corresponding number of potential improvements in systems, technologies can contribute, are shown in Table III. For example, technology 6 (composites processing) contributes a single potential system improvement within three problem areas, i.e., weight reduction, manufacturing costs, and ablation.

### *The Mathematical Model*

A mathematical model is developed to combine subjective and objective criteria, and technology ratings toward the criteria, in order to obtain composite multicriteria indices for the technologies.

The simplest model used to develop a composite multicriteria index is the additive linear model. A technology is rated according to its contribution toward each of the criteria, the ratings are weighted according to the importance of the criteria and the weighted ratings of each technology are accumulated over all criteria.

The composite multicriteria index, or technology measure ($TM_j$) for technology $j$, can be expressed mathematically in terms of objective and subjective criteria weights and technology ratings as follows:

$$TM_j = \sum_{i=1}^{n} ws_i \cdot x_{ij} + wo \cdot xo_j \quad j = 1, \cdots, m \qquad (1)$$

where

$ws_i$ is the weight for the $i$th subjective criterion

$x_{ij}$ is the rating of the $j$th technology with respect to the ith subjective criterion

wo and $xo_j$ are the objective criterion weight and the $j$th technology rating toward that criterion, respectively. (If more than one objective criterion existed a summation over all objective criteria would have been appropriate).

TABLE III
NUMBER OF SYSTEMS IMPROVEMENTS CONTRIBUTED BY TECHNOLOGIES WITHIN PROBLEM AREAS ($r_{kj}$)

| ATTRIBUTES OF "SYSTEMS NEEDS AND MILITARY UTILITY" | PROBLEM AREAS (k) | TECHNOLOGIES (j) | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| Survivability | 1. Crashworthiness | | | | | | | | | | | | | | | | | | | | | | |
| | 2. Ballistic protection | 1 | | | | | | | 2 | 1 | | | | 4 | | 1 | | | | | 3 | | |
| | 3. Camouflage | | | | | | | | 1 | | | | | | | | | | | | | | |
| | 4. Directed energy hardening | | | | 1 | | | | 1 | | | | 3 | | | | | | | | | | 1 |
| | 5. IR signature reduction | | | | | | | | | | | | | | | | 1 | | | | | | |
| | 6. NBC protection | | 1 | | 1 | | | | 1 | | 1 | | | | | | | | | | | | |
| | 7. Radar absorption | | | | | | | | | | | | | | | | | | | | | | |
| Weight reduction | 8. Weight reduction | | | | | | 1 | | 9 | | 4 | | | | | 1 | | | 1 | | 3 | | |
| Reliability Availability Maintainability (RAM) | 9. Design methodology | | | | | | | | 1 | | | | | | | | | | | | | | |
| | 10. Life prediction | | 1 | | | | | | | | 1 | | | | | | | | | | | | |
| | 11. Maintainability | | | | | | | | | | | | | | | | | | | | | | |
| | 12. Material selection | 1 | 1 | | 1 | | | | | | | | | | | | | | | | | | |
| | 13. Material standards | | | | | | | | | | | | | | | | | | | | | | |
| | 14. Reliability | 2 | 3 | | | 1 | | 6 | 1 | 1 | 1 | | | | | | | | | | 1 | | |
| Component life (Endurance) | 15. Corrosion | | | 1 | | | | | | | | | | 1 | | | | | | | | | |
| | 16. Environmental degradation | | 2 | | | | | | | | 2 | | | | | | | | | | | 3 | |
| | 17. Erosion | | | | | | | | 1 | | | | | | | | 1 | | | | | 2 | |
| | 18. Fatigue | | | | | | | | | | | | | | | | | | | | | | |
| | 19. Wear | | 5 | | | | | | 2 | | | | | | | | | | | | | | |
| Cost reduction | 20. Design costs | | | | | | | | | | | | | | | | | | | | | | |
| | 21. Manufacturing costs | | | | | | 1 | | 1 | | | | 1 | 3 | 2 | 3 | | 3 | | | | | |
| | 22. Material costs | | | | | | | | | | | | | | | | | | | | | | |
| Strength and thermal resistance (Structure) | 23. Adhesion | 1 | | | | | | | | | | | | | | | | | | | | | |
| | 24. Residual stress | | | | | | | | | | | | | | | | | | | | | | |
| | 25. Structural integrity | | | | | | | | | | | | | | | | | | | | | | |
| | 26. Toughness | | | 1 | | | | | | | | | | | | | | | | | | | |
| | 27. Ablation | | | | | | 1 | | | | | | | | | | | | | | | | |
| | 28. High temp performance | 1 | 1 | | 1 | | | | | | | | | | | | | | | | | | |
| | 29. Thermal shock resistance | | | | | | | | | | | | | | | | | | | | | | |
| Optical characteristics | 30. Optical characteristics | | | | | | | | | | | | | | | | | | | | | | |

In order to maintain parity among all criteria, objective and subjective, the ratings $x_{ij}$ and $xo_j$ have to be normalized, i.e.,

$$\sum_{j=1}^{m} x_{ij} = 1 \text{ for } i = 1, \cdots, n \tag{2}$$

and

$$\sum_{j=1}^{m} xo_j = 1 \tag{3}$$

The normalization condition on the technology ratings with respect to each criterion ensures that the objective criterion ratings are compatible to the subjective criteria ratings. A similar approach has been used by Sharif and Sundararajan [18] in a situation in which some of the criteria were quantitative and some were qualitative.

In addition, the criteria weights are normalized, i.e.,

$$\sum_{i=1}^{n} ws_i + wo = 1.$$

### *Determination of Weights and Technology Ratings*

The weights for criteria, problem areas and criteria intensities (to be defined later in this section) were determined by the previously mentioned (AHP). The AHP was developed by Saaty in the mid-Seventies [16]. It is a flexible and powerful tool for prioritizing or ranking alternatives. It is particularly useful when the criteria are non-measurable or qualitative in nature [17]. In these situations AHP is less burdensome than other more sophisticated approaches, such as the multiattribute utility (MAU) theory [9]. The AHP has been applied to a variety of priority settings and resource allocation problems in marketing [20], new product development [14], electric power allocation [15], industrial R&D project selection and resource allocation [11], among others.

The criteria weights $ws_i$ $i = 1, \cdots, n$ and wo were determined by the AHP using a matrix of pairwise comparisons reflecting the relative importance of the criteria with respect to the main objective or focus, defined as, "Accomplishment of the Army mission through the use of advanced materials technology."

In order to rate the technologies with respect to each subjective criterion $i = 1, \cdots, n$, four performance rating levels (1, 2, 3, 4) were established. The four rating levels, referred to as "criteria intensities", were defined by the management of MTL as shown in the third column of Table II. The weights of the four levels, $v_{i1}, v_{i2}, v_{i3}, v_{i4}$, for each subjective criterion $i$ were determined using pairwise comparisons matrices, one for each criterion $i$. These weights are used in the next section for rating the technologies, for example if technology $j$ is rated at intensity level 1 with respect to criterion $i$, then $x_{ij} = v_{i1}$.

It should be pointed out that if the number of technologies was small, less than or equal to seven, the technologies could have been directly pairwise compared with respect to each criterion. In the latter case criteria intensities and technology ratings could have been unnecessary. The AHP imposes a restriction on the maximum number of elements (7) that can be pairwise compared [17]. Thus, the number of technologies affected the choice of the mathematical model to be used in this study. A similar "rating" approach is used by Liberatore [11] in evaluating a large number of projects.

The technology ratings $xo_j$ with respect to the objective criterion, "systems needs and military utility", were obtained by using the quantitative data developed by the TWG which are displayed in Table III. The rating $xo_j$ depends on the degree technology $j$ addresses problem areas and the relative importance of these problem areas. The degree by which technology $j$ addresses problem area $k$, $f_{kj}$, was modeled as a piecewise concave linear function of the number of potential improvements in systems within problem area $k$, $r_{kj}$, as follows:

$$f_{kj} = \begin{cases} r_{kj} & \text{if } r_{kj} \le 1 \\ 1 + (r_{kj} - 1)/2 & \text{if } r_{kj} > 1 \end{cases} \qquad k = 1, \cdots, p \;\; j = 1, \cdots, m. \quad (4)$$

For a given number of systems improvements, a technology is favored if it covers many problem areas. This was taken into consideration in the definition of the measure $f_{kj}$. The number 1's choice in the above formula is derived from an analysis of the TWG data and an appreciation of the importance for a technology to address a wide range of problem areas. A simple observation will reveal that 1 is by far the most common occurrence and a simple arithmetic calculation will show an average of 1.78 potential improvements in a problem area, with both the median and mode being 1. A technology that has been applied a high number of times to one area in a particular year would not necessarily find use in another given year. A technology that has made improvements in many areas would more likely find continuous use. The rating of technology $j$, with respect to "systems needs and military utility" is obtained as a weighted sum of the $f_{kj}$'s, over all problem areas, i.e.,

$$xo_j = \sum_{k=1}^{p} u_k \cdot f_{kj} \;\; j = 1, \cdots, m \quad (5)$$

where $u_k$ is the weight for problem area $k$, $k = 1, \cdots, p$.

The weights for problem areas, $u_k$, could have been obtained directly using a pairwise comparison matrix, if $p \le 7$, a restriction of AHP, mentioned earlier. Since the actual value of $p$ was 30, the problem areas were grouped into clusters, referred to as "attributes" of the objective criterion, as shown in Table III. Most of these attributes were already used by MTL in defining its mission toward the Army needs. Since the number of problem areas within each attribute was at most seven, and the number of attributes was seven, the AHP was applied without any modification to derive weights for problem areas. A pairwise comparison matrix of attributes with respect to the "systems needs and military utility criterion" is required to yield attribute weights. In addition, one pairwise comparison matrix of problem areas within each attribute is required to yield problem area weights with respect to the attribute. The overall weight $u_k$ of problem area $k$ with respect to the objective criterion, is obtained as the product of the weight of the attribute the kth problem area belongs to, and the weight of problem area $k$ with respect to that atttribute. A hierarchical representation of the MTL technologies prioritization model is shown in Figs. 1 and 2.

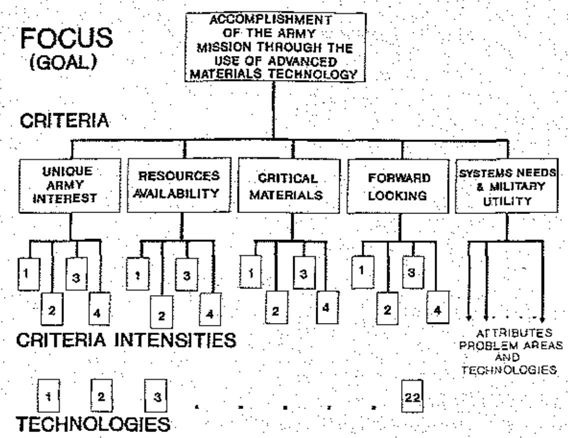

Fig. 1. Hierarchical representation of subjective criteria.

## Application of the Model

After the formulation of the mathematical model was completed, the management of MTL decided to proceed with plans to use the model. From its conception, the model was intended to be driven by the expertise of personnel from within MTL. There were two reasons for this: 1) It was believed that the laboratory personnel would be more

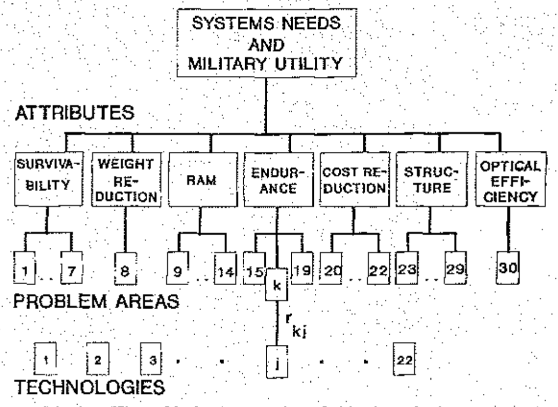


Fig. 2. Hierarchical representation of objective criterion.

amenable to an evaluation procedure with which they had direct input; and 2) only insiders would have a true feeling for the kinds of technological work which were feasible and practical for the Laboratory.

The first action was to brief the Director, Associate Director, and Commander (Deputy Director) of the installation as well as the three division Directors. There was an extensive discussion of pairwise comparisons in terms of their use and logic. Each division was asked to appoint representatives to submit data for the model. The panel of representatives from each division consisted of the Directorate Chief and their subordinate branch chiefs.

One week later each division was visited and presented with a followup briefing, at which time pairwise comparison forms for the criteria intensities were distributed. Each representative of the division received an identical pairwise comparison form. After being briefed on the specific requirements of this stage, each member proceeded to fill in the criteria intensities matrices independently. When all the respondents had completed the forms, the next stage began, a consensus. All the forms were collected anonymously. A series of similar pairwise comparison boxes were drawn on the conference room board and all of the numbers that had been submitted were entered into the boxes for all to view. The panel members were asked to reach a consensus. This procedure was repeated for each division.

During the next three weeks the divisions provided the necessary pairwise comparison matrices for the criteria, attributes, and problem areas within each attribute. Again each representative filled in the forms independently and a consensus was reached within each division.

The software package Expert Choice (see Forman *et al.* [5]) was used next to generate the weights. Expert Choice is a user-friendly, interactive software package which computes weights from pairwise comparison matrices. The generated weights for the criteria ($ws_i$, $i = 1, \cdots, 4$, and $wo$), criteria intensities ($v_{i1}$, $v_{i2}$, $v_{i3}$, $v_{i4}$, $i = 1, 2, 3, 4$), attribute and problem area weights $u_k k = 1, \cdots, 30$, for the M&SI division are displayed in Table IV.

The final step was to actually rate the technologies with regard to the subjective criteria. The division representatives were presented with a table containing all 22 technologies and supplied with a list of the criteria and a short description of the four intensity levels for each criterion (see Tables I and II). The resulting ratings after concensus for the M&SI division are shown in Table V. Ratings were not averaged for two reasons. First, since the criteria intensity values were generated for discrete integer values, an average of the responses is likely to fall between two of the calculated values. This will force the model user into attempting some kind of interpolation to find the corresponding value for the non integer input. Linear interpolation would not be accurate although easy to apply. More sophisticated approaches would be time consuming and would make the model difficult to use. Secondly, the model developers considered a consensus to be far more meaningful that a simple average. In using an average you have the distinct possibility of reaching a figure with which no member of the group would agree. In reaching a consensus you achieve an opinion with which all members should be comfortable.

The variance in the ratings is low. This is likely to occur when reaching a consensus opinion. Individuals did select the extremes (1's and 4's) but when the consensus was reached, in most cases, the extreme opinions were moderated. All opinions were important factors in reaching the final decision so the lack of a significant percentage of high and low numbers does not indicate these opinions were lost when the consensus was reached.

In the area of "Resources Availability", it can be seen in Table V that respondents felt that resources for all technologies would be available either at MTL or easily obtained elsewhere. Since the list of technologies represented all ongoing research programs, it is obvious that the means were available for this research work to be performed. Consequently, the ratings fell between 1 and 2.

In the area of "Forward Looking", respondents were asked to judge each technology in terms of its potential to attract and retain competent engineers and scientists as a result of the research being advanced in the field. All technologies scored well in under this criterion because the work performed at MTL is all of an advanced nature even in the more traditional technologies. This results from MTL's main mission, stated in the introduction.

In the area of "Unique Army Interest", the ratings vary from 2 to 4. It is important to note that no technology received a rating of 1, indicating its unique application to the Army's requirements. Basic research, such as performed at MTL, is by nature of wide application. Therefore, MTL's technologies are not exclusive to the Army. As a result, there is much collaborative research between MTL and the university community as well as with small businesses.

Under the criterion "Critical Materials,", the ratings vary from 1 to 3. In this category there is the most diversity. This results from the fact that the projects which fall under the different technology areas have very different effects on the use of critical materials. No technology, however, received the rating 4, indicating that it actually would increase U.S. dependency on critical materials.

The derived weights (Table IV) together with the number

TABLE IV
WEIGHTS OBTAINED FROM M&SI PAIRWISE COMPARISON MATRICES

| SUBJECTIVE CRITERIA (i) | WEIGHT $ws_i$ | CRITERIA INTENSITIES $v_{i1}$ | $v_{i2}$ | $v_{i3}$ | $v_{i4}$ |
|---|---|---|---|---|---|
| 1. Unique Army Interest (UAI) | .235 | .533 | .272 | .139 | .056 |
| 2. Resources Availability (RA) | .178 | .534 | .310 | .113 | .043 |
| 3. Critical Materials (CM) | .073 | .586 | .272 | .094 | .048 |
| 4. Forward Looking (FL) | .093 | .614 | .248 | .101 | .037 |

| OBJECTIVE CRITERION | wo |
|---|---|
| Systems Needs and Military Utility (SN&MU) | .421 |

ATTRIBUTES AND PROBLEM AREAS

| | SURVIVABILITY (.282) | | | | | | | WT. RED. (.221) | RAM (.148) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| k | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| $u_k$ | .036 | .055 | .028 | .047 | .039 | .049 | .028 | .221 | .017 | .033 | .037 | .021 | .015 | .026 |

| | ENDURANCE (.145) | | | | | COST RED. (.1) | | | STRUCTURE (.084) | | | | | | | OPT. CH. (.02) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| k | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| $u_k$ | .036 | .036 | .018 | .028 | .026 | .041 | .026 | .033 | .009 | .015 | .021 | .017 | .004 | .009 | .009 | .020 |

TABLE V
M&SI TECHNOLOGY RATINGS WITH RESPECT TO THE SUBJECTIVE CRITERIA

| Technologies | Unique Army Interest | Resources Availability | Critical Materials | Forward Looking |
|---|---|---|---|---|
| 1. Joining | 3 | 2 | 3 | 1 |
| 2. Elastomers | 2 | 1 | 2 | 2 |
| 3. Metals | 3 | 1 | 3 | 2 |
| 4. Polymers | 2 | 1 | 2 | 2 |
| 5. Organics processing | 3 | 1 | 2 | 1 |
| 6. Composites processing | 2 | 1 | 2 | 1 |
| 7. Quality assurance | 2 | 1 | 2 | 2 |
| 8. Design and engineering properties/methods | 3 | 2 | 2 | 2 |
| 9. Analytical and numerical methods | 3 | 1 | 2 | 1 |
| 10. Resin matrix composite | 3 | 1 | 2 | 2 |
| 11. Fibers | 3 | 2 | 2 | 2 |
| 12. Electronics/electro- optics | 3 | 2 | 3 | 2 |
| 13. Metal processing | 3 | 1 | 2 | 2 |
| 14. Mechanics of processing | 3 | 2 | 2 | 2 |
| 15. Ceramic processing | 3 | 1 | 2 | 1 |
| 16. Ceramics | 3 | 1 | 1 | 2 |
| 17. Automated process control | 4 | 2 | 2 | 1 |
| 18. Ceramic matrix composite | 2 | 1 | 1 | 1 |
| 19. Powder processing | 2 | 1 | 2 | 1 |
| 20. Metal matrix composite | 2 | 1 | 2 | 1 |
| 21. Surface treatment/coatings | 3 | 2 | 2 | 2 |
| 22. Macro composites | 3 | 2 | 2 | 2 |

of systems improvements (Table III), and the technology ratings with respect to the subjective criteria (Table V), were loaded on to the DBASE III database system for processing. A table for the $f_{kj}$'s was generated from Table III ($r_{kj}$), according to (4). The technology ratings with respect to "systems needs and military utility," $xo_j$, were obtained by vector multiplication on the database according to (5). A table for the criteria intensities was generated from Table V, by replacing each technology rating (1, 2, 3, or 4) with the corresponding criterion intensity ($v_{i1}$, $v_{i2}$, $v_{i3}$, or $v_{i4}$). All technology ratings were entered onto another database and were normalized according to (2) and (3).

The normalized technology ratings with respect to all criteria for the M&SI division, are shown in Table VI.

TABLE VI
TECHNOLOGY NORMALIZED RATINGS FOR M&SI DIVISION

| Technologies ($j$) | UAI($ws_1$ = .235) ($x_{1j}$) | RA($ws_2$ = .178) ($x_{2j}$) | CM($ws_3$ = .073) ($x_{3j}$) | FL($ws_4$ = .093) ($x_{4j}$) | SN&MU($wo$ = .421) ($xo_j$) |
|---|---|---|---|---|---|
| 1. Joining | 0.041 | 0.035 | 0.017 | 0.040 | 0.027 |
| 2. Elastomers | 0.081 | 0.035 | 0.049 | 0.040 | 0.059 |
| 3. Metals | 0.041 | 0.035 | 0.017 | 0.040 | 0.010 |
| 4. Polymers | 0.041 | 0.060 | 0.049 | 0.040 | 0.025 |
| 5. Organic proc | 0.041 | 0.060 | 0.049 | 0.040 | 0.005 |
| 6. Composite proc | 0.041 | 0.060 | 0.049 | 0.040 | 0.050 |
| 7. QA | 0.081 | 0.035 | 0.017 | 0.040 | 0.018 |
| 8. Des and eng prop | 0.041 | 0.035 | 0.049 | 0.040 | 0.286 |
| 9. Anal and num met | 0.041 | 0.060 | 0.049 | 0.040 | 0.016 |
| 10. Resin M com | 0.041 | 0.060 | 0.049 | 0.040 | 0.142 |
| 11. Fibers | 0.041 | 0.035 | 0.049 | 0.040 | 0.000 |
| 12. El/elec opt | 0.041 | 0.035 | 0.017 | 0.040 | 0.024 |
| 13. Metal proc | 0.041 | 0.035 | 0.049 | 0.040 | 0.052 |
| 14. Mech proc | 0.041 | 0.035 | 0.049 | 0.040 | 0.008 |
| 15. Ceramic proc | 0.041 | 0.060 | 0.049 | 0.040 | 0.065 |
| 16. Ceramics | 0.041 | 0.060 | 0.105 | 0.040 | 0.011 |
| 17. Auto proc C | 0.017 | 0.035 | 0.049 | 0.099 | 0.010 |
| 18. Ceramic M com | 0.081 | 0.035 | 0.049 | 0.040 | 0.044 |
| 19. Powder proc | 0.041 | 0.060 | 0.049 | 0.040 | 0.000 |
| 20. Metal M com | 0.041 | 0.060 | 0.049 | 0.100 | 0.115 |
| 21. Surface treat | 0.041 | 0.035 | 0.049 | 0.040 | 0.020 |
| 22. Macro com | 0.041 | 0.035 | 0.049 | 0.040 | 0.009 |

Finally, the basic equation (1) was applied to yield the technology measures $TM_j\ j = 1, \cdots, m$ which after being sorted in descending order are displayed in the second column of Table VII. This process, repeated for the other two divisions, yielded the technology measures displayed in the fourth and sixth columns of Table VII. A numerical example for the calculation of the measure of one of the technologies, "Design and Engineering Properties/Methods" ($j = 8$) follows: The values $r_{kj}$ of Table III after adjustment according to (4) yield $f_{28} = 1.5$, $f_{88} = 5$, $f_{19,8} = 1.5$, $f_{k8} = r_{k8}\ k \neq 2, 8, 19$. Substituting $f_{k8}$ and problem area weights $u_k$, $k = 1, \cdots, 30$ (Table IV) into (5) the technology rating $xo'_8 = 1.437$ is obtained, where "$'$" denotes a rating before normalization. In a similar way all other technology ratings $xo'_j\ j \neq 8$ are obtained. The normalization (3) converts the rating to $xo_8 = .286$. The criteria intensities corresponding to technology ratings for $j = 8$ (Table V) are found in Table IV, $x'_{18} = .139$, $x'_{28} = .310$, $x'_{38} = .272$, and $x'_{48} = .248$. These ratings after normalization according to (2) become $x_{18} = .041$, $x_{28} = .035$, $x_{38} = .049$, and $x_{48} = .040$, as shown in Table VI.

Finally, (1) yields the technology measure

$$TM_8 = (.235)(.041) + (.178)(.035) + (.073)(.049) + (.093)(.040) + (.421)(.286) = .144$$

A consensus was never attempted among the three divisions. The top management at MTL, had for the most part worked for one of the divisions in their careers and were acutely aware of the rivalry that existed among the three divisions. It was felt that much could be learned from comparing the results of the three divisions separately and not much could be gained by trying to reach an almost impossible consensus among the three divisions. The sensitivity given to division rivalry is very important. The model allowed each division to provide data independently of the others but with the knowledge that skewing the result in their favor would easily be detected in a computation of the results. This encouraged objective input. The model developers and MTL management knew that there would be a natural tendency, even when trying to be objective, to favor technologies in their own area. As it turned out, there was quite a bit of similarity in the results. "Design and Engineering Properties" was the highest rated technology by each division. In the top five technologies, three were in common and in the top ten, six were in common with all three divisions (see Table VII). This results largely from the dominant weight each division gave the objective criterion "Systems Needs and Military Utility". The differences were also fairly easy to understand. Quality assurance fared much better with M&SI than OML, which is no surprise since M&SI performs all the quality assurance work. "Metal Matrix Composite" scored highest in the MCL division, again no surprise since it is a technology of exclusive interest to that division.

Inconsistency is a natural human trait. In any comparison made by humans some inconsistencies will arise. Expert Choice and AHP expect this occurrence and account for it by generating an inconsistency index. The inconsistency index for OML was 0.02, for M&SI was 0.05, and for MCL was 0.12. The developers of Expert Choice, Forman *et al.* [5], state that "if the inconsistency index is considerably more than .10 (say 0.20) then a reexamination of judgments may be in order". Since the index for only one division was slightly above 0.10 while the indices for the other two divisions were considerably below 0.10, the indices were considered acceptable without reexamination of judgments becoming necessary.

There was interest in combining the results of the three decision makers (divisions) to develop aggregate technology measures. One idea involved combining the results of the

TABLE VII
TECHNOLOGY MEASURES FROM DATA SUPPLIED BY EACH DIVISION AND AGGREGATE MEASURES

| Technologies ($j$) | $TM_j$ (M&SI) | Technologies ($j$) | $TM_j$ (MCL) | Technologies ($j$) | $TM_j$ (OML) | Technologies ($j$) | $TM_j$ Aggregate |
|---|---|---|---|---|---|---|---|
| 1. Des and eng prop | 0.144 | 1. Des and eng prop | 0.120 | 1. Des and eng prop | 0.116 | 1. Des and eng prop | 0.126 |
| 2. Resin M com | 0.088 | 2. Metal M com | 0.100 | 2. Resin M com | 0.069 | 2. Metal M com | 0.081 |
| 3. Metal M com | 0.082 | 3. Metal proc | 0.068 | 3. Metal M com | 0.064 | 3. Resin M com | 0.074 |
| 4. Elastomers | 0.057 | 4. Resin M com | 0.067 | 4. Metal proc | 0.062 | 4. Metal proc | 0.058 |
| 5. Ceramic proc | 0.055 | 5. Ceramic proc | 0.064 | 5. Composite proc | 0.059 | 5. Ceramic proc | 0.058 |
| 6. Ceramic M com | 0.050 | 6. Ceramic M com | 0.055 | 6. Ceramic proc | 0.054 | 6. Composite proc | 0.053 |
| 7. Composite proc | 0.049 | 7. El/elec opt | 0.051 | 7. Elastomers | 0.050 | 7. Elastomers | 0.047 |
| 8. Metal proc | 0.045 | 6. Composite proc | 0.052 | 8. Joining | 0.044 | 8. Ceramic M com | 0.047 |
| 9. Polymers | 0.039 | 9. Joining | 0.048 | 9. Organic proc | 0.044 | 9. Joining | 0.040 |
| 10. QA | 0.038 | 10. Ceramics | 0.041 | 10. Polymers | 0.045 | 10. El/elec opt | 0.040 |
| 11. Ceramics | 0.037 | 11. Macro com | 0.037 | 11. Mech proc | 0.040 | 11. Polymers | 0.035 |
| 12. Anal and num met | 0.034 | 12. Elastomers | 0.036 | 12. El/elec opt | 0.039 | 12. Ceramics | 0.034 |
| 13. Joining | 0.032 | 13. QA | 0.034 | 13. Auto pro C | 0.039 | 13. Anal and num met | 0.034 |
| 14. Surface treat | 0.031 | 14. Anal and num met | 0.033 | 14. Surface treat | 0.037 | 14. QA | 0.032 |
| 15. El/elec opt | 0.031 | 15. Metals | 0.029 | 15. Ceramic M com | 0.037 | 15. Surface treat | 0.032 |
| 16. Organic proc | 0.030 | 16. Surface treat | 0.029 | 16. Anal and num met | 0.034 | 16. Macro com | 0.032 |
| 17. Powder proc | 0.028 | 17. Mech proc | 0.028 | 17. Macro com | 0.033 | 17. Mech proc | 0.031 |
| 18. Auto proc C | 0.027 | 18. Polymers | 0.026 | 18. Powder proc | 0.031 | 18. Organic proc | 0.030 |
| 19. Macro com | 0.027 | 19. Auto proc C | 0.021 | 19. Fibers | 0.027 | 19. Auto proc C | 0.028 |
| 20. Mech proc | 0.026 | 20. Powder proc | 0.021 | 20. QA | 0.026 | 20. Powder procs | 0.026 |
| 21. Metals | 0.025 | 21. Organic proc | 0.020 | 21. Ceramics | 0.026 | 21. Metals | 0.025 |
| 22. Fibers | 0.023 | 22. Fibers | 0.018 | 22. Metals | 0.022 | 22. Fibers | 0.023 |

three divisions based on funding. MTL's research fell into three categories: 6.1, Basic Research; 6.2, Applied Research; and 6.3a, Exploratory Development, each with its own funding line. The technology measures for the three divisions were weighted by their share of 6.1 funding and added to provide an aggregate technology measure. This was repeated for the 6.2 and 6.3a funding. Since there were great similarities in the final rankings by the three divisions, combining the results did not cause major ranking changes. Technologies at the top tended to stay at the top and those at the bottom tended to remain in that area. Since the weights were proportional to the divisions funding shares, the produced aggregate measures slightly favored divisions with existing large shares. Another idea was to combine the technology measures produced by the three divisions by weighting them equally (unit weight). The geometric average was used, i.e., for each technology the third root of the product of the three measures was taken. The geometric averaging is also called the Nash bargaining rule, satisfying Nash's four axions of "fairness" [13]. The resulting aggregate technology measures are shown in the last column of Table VII. Another group decision rule often used is the one based on arithmetic averaging (see Harsanyi, [8]). The ranking obtained by the last rule was identical to the one obtained by geometric averaging. This final ranking was made available to the management of MTL in funding projects within technology areas.

MTL received funding for research and development broken down in the form of work packages. The funding within a work package and the technology work required for it, was not within the control of the Laboratory management. Management exerted influence, however, by breaking the work packages down, internally, into smaller work units which could be determined and controlled from within MTL. While this did not free MTL from the burden of following the guidelines of the work package, it did allow for substantial creativity in designating work units. In addition, most managers were allowed to retain a certain amount of money to be distributed at their discretion. These funds would be very important towards the end of a fiscal year when projects (work units) were low or completely out of money. This ability to withhold and release funds and the ability to break work packages down to the work unit level allowed MTL management the means to control the funding for technologies and projects. The results of this study provided management a powerful tool by which intelligent and informed decisions could be made regarding the allocation of available funds and the selection of projects.

## SUMMARY AND CONCLUSION

The prioritization of technologies in a multitechnology government laboratory is a complex task involving to a great extent "subjective" criteria and uncertain technology contributions toward these criteria. If any objective criteria are appropriate, those should be combined in a compatible way with the subjective criteria to yield the technology measures. The AHP, through pairwise comparisons, can provide an easy and reliable method in determining the relative importance of the criteria and can be checked for consistency.

A mathematical model has been developed by the authors to prioritize the technologies at MTL. The model determines technology measures by appropriately combining weights for subjective and objective criteria and technology ratings toward the criteria. A hierarchical representation consisting of several levels of criteria and technologies was constructed. Each of the three divisions of the laboratory weighted the criteria and rated the technologies independently to develop a ranking of technologies according to the model. Although the three division rankings were not identical and technologies belonging exclusively to some divisions were slightly favored over others, the top ranking technologies were in general the same among divisions. The results from the three divisions were aggregated in a single technology ranking to be used by the management of MTL in funding projects within technology areas. A new ranking should be developed every few years to reflect technology trends and Army systems needs. Although the prioritization model was developed specifically for MTL, the whole approach including selection of criteria and determination of weights and ratings is general and can be utilized with slight modifications to evaluate and rank technologies in other research laboratories.

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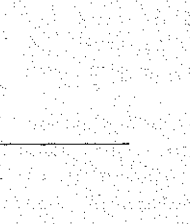

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