REDUCING LEAD-TIME THROUGH IMPROVED TECHNOLOGICAL FORECASTING:

Some Specific Suggestions for More Usefully Formulated Projections of Technological Availability

David Novick
and
Frederick S. Pardee

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David Novick*
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Frederick S. Pardee*

The Rand Corporation, Santa Monica, California

The lead-time phenomenon has been with us for many years. Since we started emphasizing its importance in long-range planning, it has become recognized in most military circles and it is starting to be incorporated into some of the more realistic assessments of major urban issues.

In spite of many attempts, however, the critical problem remains of what can be done to reduce the amount of time involved in converting technological dream to reality. In the defense environment, concern over the seemingly excessive times required to plan, define, develop, produce and deploy new weapon systems is just as severe today as it was fifteen years ago.

There undoubtedly are many reasons why it takes time to invent and innovate new approaches: Research paths frequently prove fruitless and require backtracking; obtaining resource support for an idea often requires horrendous amounts of effort; coordinating activities assigned to develop various portions of an overall system usually proves to be a substantial obstacle course, and so forth.

It seems strange that it is so difficult to explain the length of the lead-time in the development and production of aircraft and missiles. Even construction of a modern office building, while not

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a very complicated structure in comparison with military hardware, nevertheless takes significant amounts of time. Standard grades of steel are used for beams, reinforcement rods and mesh. A large number of suppliers stand ready to sell ready-mixed concrete, sheathing materials for the exterior, sash, flooring, roofing materials, and every other part of the structure. Still it takes two or three years or more to obtain bids, select a contractor team and actually construct an office building.

An engineer designing military equipment might object to what we are saying on the ground that it understates the great differences in level of difficulty in designing and constructing a simple structure, as contrasted to large, precision-made, far more complicated development programs. Modern military demands are complex and the processes of satisfying them are complicated and time consuming. Over the last century the number of steps and length of time required for development and fabrication of complete products has increased many fold. The machine-to-make-the-machine has played an increasingly important role in our methods of development and production. Specialization, mechanization, and automation, characterize modern industry, and although they speed up the processes and increase the output at the point of final assembly, if we go back a few steps in the method we immediately encounter time-consuming and investment-demanding requirements.

These problems shift the burden from an individual supplier to the total economic system and make long periods of time necessary for the accomplishment of tasks. It is easy to lose sight of the size of the pyramid at the point of final assembly and be almost unaware of the pyramidal structure involved at each succeedingly lower layer. The final product has a time as well as quantity and quality dimensions and each of the sub-pyramids has in itself a major time dimension.

INNOVATION OR INVENTION

Improvements in technology are in large part essentially innovations rather than inventions. That is, the new idea was researched and at least partially invented many years ago. The point can be easily made for those who can recall the push-button or automatic gear-shift of the Mitchell and Premier automobiles which were on the road around 1920. It was twenty-five years or so before those ideas were developed for general application to passenger automobiles. Much the same history applies in many other fields.

Military requirements have a much broader research base than is required for most commercial products. The activities must include not only new ways of doing a job--aircraft, missiles, space vehicles, etc.--but also all of the materials, components and processes involved in producing the new devices. In all of these, continuity is a paramount consideration lest a research discovery in one field be too far ahead of the essential supporting fields to permit the quick development and application of the new idea.

Furthermore, new scientific discoveries or inventions usually are just the beginning of a large number of steps required first in developing a product and then finding ways of applying the invention to either established or new ways of doing the job.

In new military systems, the time required must be made as short as possible. Shortening it requires men and resources, but no matter how much money is spent it still takes time.

In examining this critical problem, perhaps it is useful to first attempt to separate those elements of lead-time of an organizational or administrative nature from those primarily associated with technology per se. In this paper we wish to recognize the importance of administrative lag factors, but are focusing our attention on suggestions for more realistically estimating technological lags. Hopefully, these suggestions for increasing explicitness will have the effect of highlighting useful approaches resulting in reduction of times required in translating notions into operational hardware.

BASIC FRAMEWORK AND CRITERIA FOR SELECTION OF PERFORMANCE CHARACTERISTICS

The purpose of this paper then is to suggest a series of refinements in the methodology of technological forecasting. These suggestions are designed to increase the utility of information generated in such forecasts by communicating more fully both the major underlying assumptions and the sensitivity of the resulting projections. It is important to point out that our primary orientation is toward use of technological forecasting in development of information for planning and decisionmaking on research and development programs.

This interest stems originally from association with three general trends in defense systems analysis: (1) the growth of a wide variety of weapon system conceptual studies in the late 1950s, (2) force structure and posture studies in the early and mid-1960s, and (3) recent and current efforts to determine criteria for allocation of support to technology and potential subsystem development projects. Each of these analytic activities now is an important component of technical planning methodology for aerospace research and development and all require meaningful forecasts of technological potential as inputs.

One other introductory comment is in order: Whatever we have to suggest is based on the assumption that the overwhelming majority of technological improvements are evolutionary in nature; these build in a more or less orderly fashion on earlier technology; those technological achievements genuinely deserving the label "breakthrough" are rare. There exists, therefore, an underlying rationale to systematic forecasting. It is important at the outset to identify those features which we view as inherent in the basic methodology.

To develop a quantitative projection of potential advance in the state of the art, it is necessary first to select a performance characteristic or combination of characteristics which provides a satisfactorily comprehensive measure of the state of the art in a given technical area. This presupposes that actions such as the following have been taken:

- The breadth or scope of each technical area has been defined clearly. Guidelines are needed on the appropriate breadth to be used for each of several planning contexts or durations.
- A comprehensive and non-overlapping structure of all major technical areas has been developed which details the context of each individual area. For most purposes, especially those associated with military-sponsored research, the technical areas as well as the major projects within technical areas should be identified --as a minimum in terms of major defense or corporate objectives, classes of weaponry proposed to meet the more important types of anticipated threats, and product lines designed to capture potential types of markets.
- A system exists for maintaining continuity in the overall technical area structure so that any narrowing, branching, or other changes can be identified easily on an historical basis. This could take the form of a system for maintaining a running record of the original plan and its changes and a method for tracking progress against the projection.

Assuming that such an overall technical area structure has been adequately formulated, the search for characteristics suitable for quantification can then begin in earnest. The following is an illustrative list of the types of guidelines or criteria which might be developed in more precise--hopefully quantitative--form to serve as an aid in the selection of acceptable measures of performance capability:

- **Comprehensiveness**
- **Operational Significance**
- **Ease of Measurement**
- **Probable Accuracy**
- **Identification and Measurability of Interdependencies:**
  - **With Other Performance Characteristics**
  - **With Other Technical Areas**

Comprehensiveness. The characteristic or combination of characteristics selected should incorporate a high portion--perhaps some explicit percentage--of the technical approaches, and quantitatively identifiable objectives within these approaches, which are likely to be derived from research in the technical area during the time period covered by the forecast. A single variable would be preferable if it can be made to adequately represent progress in the area. As a practical matter, the number of variables selected usually should not exceed three or four.

Operational Significance. Preferably the characteristic or characteristics selected should bear a direct relationship to a specified need, in the military context to a major design specification such as those which might appear in future system operational requirements. Examples of these are measurements like range, speed, accuracy, and payload capability.

Ease of Measurement. Consideration should be given to the ease with which values that are to be shown in the projections can be measured. Likely sources for such data include research activities which involve the use of mathematical simulation of the operating characteristics of the future hardware; partial scale or partial duration tests, including breadboards and mockups; or full scale and full duration testing.

Probable Accuracy. Evaluation of this facet might be exercised using informal checks for reasonableness, formal tests of statistical validity, or some intermediary means.

Identification and Measurability of Interdependencies. In some instances, a pacing characteristic can be identified and other variables related to it. This often is difficult, however, since the pacing item may change as performance levels move from one portion of the range to another. For example, in aircraft design, propulsion developments--measured by acceleration or thrust levels--may be the pacing item at one part of the speed regime, whereas at higher levels, heat resistant material--measured by temperature--may be the pacing comresistant material--measured by temperature--may be the pacing component. This type of interdependent relationship is also identifiable at lower subsystem levels.

In addition to selecting the characteristic or characteristics which will be quantified in the projection, it also may prove useful to provide a brief statement or list of other important characteristics or considerations which should be evaluated qualitatively when assessing a given technical area.

The following are two examples in the hard sciences which use a single performance measure to represent the technical advance. These are taken from impressive work done several years ago at Wright Field.

Obviously, there are certain additional difficulties in attempting to select characteristics which can be used for quantitative projection in the soft sciences. It may be that there are some soft

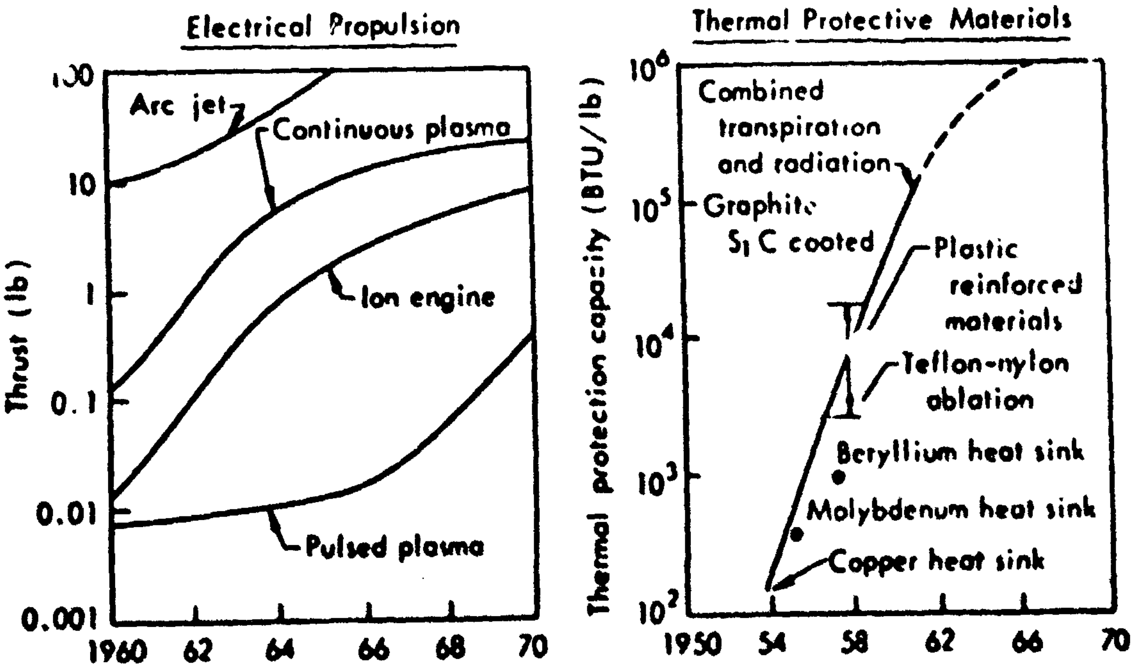

Fig. 1—First-order technological projections in the "hard" sciences

science areas which simply cannot be handled in this fashion. With a little ingenuity, however, a great deal can be done in attempting to quantify research in many of these areas.* For a project in the life sciences, for example, one might develop some quantitative measure of knowledge attained, or success in training a living creature to adapt to increasing duration in an environment of zero gravitational force. Or perhaps one could demonstrate relaxation under conditions of confinement, starting with an allowance for change in posture, then limited movement, then limitations of pressurized chambers of increasing dimensions, 10, 20, or 50 feet in diameter. Or one might plot some comprehensive measure or measures of improvements in the specifications of successfully constructed space suits. Admittedly, each of these possibilities depends to some extent upon identification of the "soft" science research involved as well as the eventual hardware required. This need not always be the case. Assume an example at the other extreme. Although we are not necessarily recommending it, even in the mathematical sciences, progress might be forecast in a quantitative fashion--at least for the more specific projects. Examples might include the size and/or complexity of the mathematical programming problem for which a general solution may be obtained, or a measure of the number of levels, the flexibility of functional forms, or the number and extent of the interdependencies which can be handled in projected extensions of decomposition techniques.

UNIFORMITY IN TIME FRAMES AND RESEARCH STATUS POINTS

In forecasting development of performance characteristics within each technical area, it is important that uniformity be obtained both in the time period covered and the phase of development which is plotted.

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*Such an attempt also may have the advantage of improving the focus of research within the area, that is, make it a bit "harder" or more firm and hence more clearly worthy of additional support.

In preparing a series of projections to be used in a given major planning exercise, one should settle on a standard time period. This should be maintained throughout the study to measure each technical area. For example:

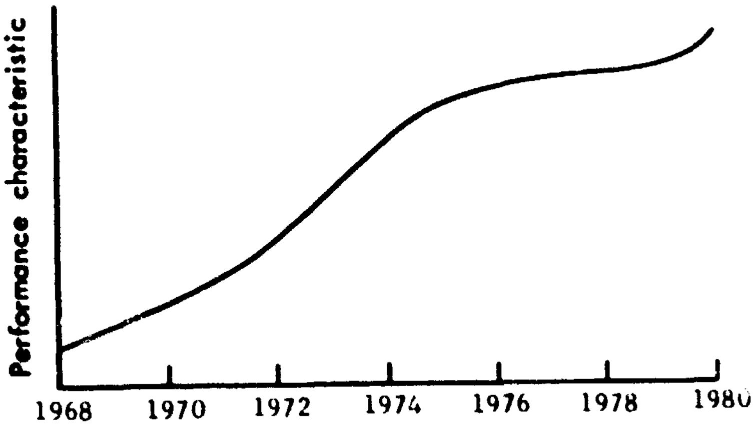

Fig.2—Illustrative standard time period to be used in projections

For closer-in projections it may be desirable to plot anticipated progress for shorter increments of time although to do so may imply greater accuracy than really is possible. In making such a suggestion, the objective is to ensure clarity in the meaning of the projection rather than to imply precision about uncertain technological advances.

In the absence of explicit assumptions, a second source of unnecessary imprecision is misunderstanding of the state to which the level of performance identified actually will have been developed and tested by a given point in time. The plot point might represent an analytic effort indicating that no violation of basic physical law would be required or that first full-scale production would be completed. In many instances, such a series of points can extend over a period of several years. An illustrative list from which to select the one or more major events to be plotted, is as follows:

(1) Analysis indicates that no violation of known physical law would be required.

(2) Technical feasibility of new approach proven.

  (2a) By paper studies (mathematical analyses, optimization studies, etc.).
  (2b) By small scale and/or short duration test.
  (2c) By full scale full duration test.
  (2d) By enough full scale, full duration tests to insure an adequate size sample.

(3) Engineering design of full major subsystem complete.

(4) Prototype of complete major subsystem thoroughly tested.

(5) Improvement integrated into total system.

  (5a) On paper.
  (5b) First test completed successfully.
  (5c) Total test series completed successfully.

(6) Production redesign completed.

(7) Production facility completed.

(8) First production units produced at quantity rates ready for delivery.

And as will be discussed subsequently:

(9) Conversion from technical feasibility to commerical profitability, as either a good or service.

This list may be more lengthy than will be required in a set of guidelines for preparation of technical projections. Its full detail is included here to emphasize the extent of the phases in the development process. In many instances it would be most logical to plot event number 2d in the list; that is, the technical feasibility of the approach has been demonstrated through a statistically adequate program of full-scale tests. At this point the technology is available to the systems engineer for inclusion in new overall system developments. If event 2d is to be used as the standard in a forecasting exercise, obviously any exceptions to this practice must be clearly identified in order that the various projections in an overall package can be meaningful.

EXPLICIT TREATMENT OF UNCERTAINTIES

Up to this point, we have furnished a few rudimentary suggestions to aid consistency and uniformity in the basic projections. Current emphasis in adhering to such objectives varies widely but in many large-scale planning efforts are still only implied rather than spelled out explicitly in forecasting guidelines.

Turning now to the treatment of uncertainty, it is reasonable to assert that attempts to deal with this consideration are infrequently handled in an explicit fashion. This is not to say that forecasters are unmindful that their function is an uncertain one. Rather that preparing forecasts is not a very widespread practice and to specify estimates in terms of high, mid, and low points, confidence limits, or inclusion of qualitative commentary on the probable range accompanying such estimates is a refinement yet to be accomplished. We suggest, however, it may, in fact, be easier for an expert in a given field to prepare such a range than it is to identify a specific single value, and that, by doing it confidence in the resulting projection frequently would be considerably enhanced.

A few methods for incorporating such information on uncertainty are provided in the following simple graphs.

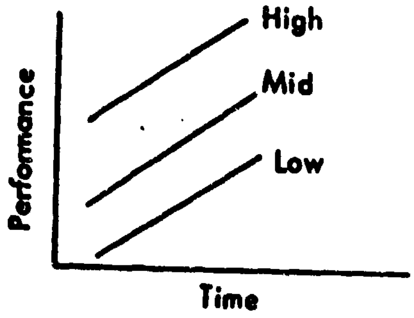

Fig. 3 - Incorporation of High, Mid and Low Estimates of Progress

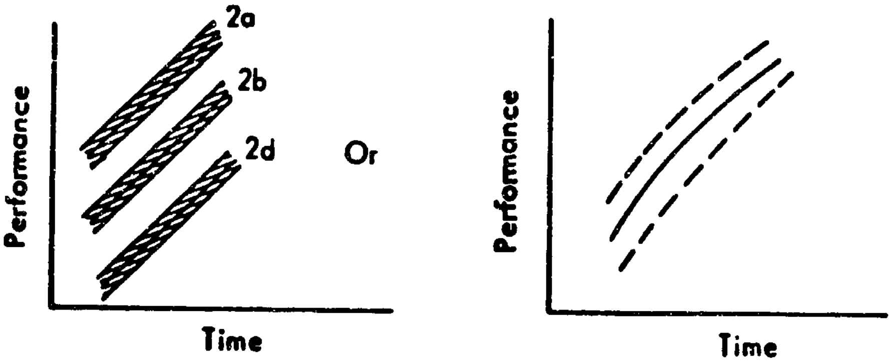

Fig. 4 - The Use of Bands or Informal Confidence Limits

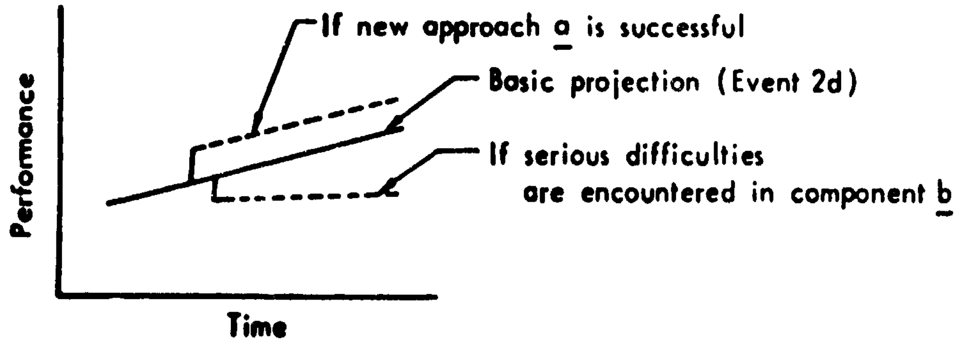

Fig. 5 - Identification of Anticipated Results if Selected Special Circumstances Occur

Such projections also may be accompanied by information which will provide an additional approximation of the sensitivity of the estimates. For example,

Check the appropriate column

(1) Likelihood of

	0	.1	.2	.3	.4	.5	.6	.7	.8	.9	1
(a) Meeting the projection, assuming adequate resources are applied.[*]											
(b) Exceeding the projection by 25%,[**] (same resource assumption).									[a]		
(c) Falling short by 25%,[**] (same resource assumption)											

(2) Probable results if

(a) The funding were doubled each year over total project life.

Average percentage increase ____%[***]

(b) The funding were cut in one-half over project life.

Average percentage increase __ %[***]

(c) And/or include a statement covering any special benefits which might be obtained either by revising the timing of funding support or by applying additional resources selectively at certain key points during development.

Certainly far more formal probabilistic tools are also available to the forecaster if he is not fearful of the spuriousness in accuracy which they may imply. At present, in the majority of instances, if one is required to make the choice, it probably makes more sense to place major emphasis on developing additional sensitivity ("what if") information

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[*] Sufficient, but not excessive. Specific interpretation left to the forecaster.

[**] A substitute percentage may be inserted in cases where 25% is clearly reasonable.

[a] Values above .5 would indicate either that the basic projection is in error or that an "inadequate" resource application was assumed.

[***] Or use a curve, plotting percentage increase by year, if an average value would be misleading.

such as that described below rather than to introduce more elaborate probabilistic refinements.

THE PROBLEM OF INTERDEPENDENCIES

Of all the methodological issues facing the technological forecaster, the problem of interdependencies is probably the most vexing. We would be naive to imply that we had anything approaching a full solution. However, the following discussion and suggestions should provide a start to dealing with the issue.

The nature of the interdependency problem can be illustrated in simplified form by the following example taken from the propulsion field. Propulsion systems can be designed for long life or for high acceleration. To some extent these two objectives are contradictory, yet in attempting to quantify state-of-the-art advance, it probably is necessary to incorporate both of these variables into the projection. Assume for purposes of illustration that these two characteristics in combination provide a comprehensive measure of the overall potential of the mode of propulsion being examined. It then is necessary to make an assumption similar to one of the following concerning interdependency:

(a) That time to failure--as a measure of design life--will remain at current maximum levels and all improvement will take the form of increased acceleration capability, or vice versa;

(b-c) That design life and acceleration will increase in (b) a constant ratio or (c) other prespecified relationship; or

(d) That since the need for increased acceleration (or design life) can be justified more substantively than the need for the other capability, therefore performance improvements will be dictated by demand. Thus, required increases in acceleration will be plotted first as the dominating characteristic, perhaps including a maximum or plateau at some point. Then assuming this pattern of development of acceleration capability, possibilities for improvement in design life will be estimated.

It is important to recognize both (a) that such projections probably can be meaningful only within the basic mode of propulsion--changes in mode may place the projection in a new flight regime[*]--and (b) that no provision has been made for the possibility of a genuine breakthrough--reserving this term for very special scientific advances. In addition, as already inferred above, any such time-phased projections are dependent upon the priority and consequent resource support which is assigned. Probably the most feasible way to deal with this interdependency problem is to search out dominant relationships which can be expressed simply and to ignore lesser interdependencies.

The following are a series of alternate approaches to incorporate interdependencies into projections, each representing an increasing level of sophistication:

(1) The use of narrative indicating that the major performance characteristics are related but not specifying the precise nature of the relationship.

(2) Plotting separately each of the three or four major characteristics which are interrelated but placing the charts in juxtaposition and accompanying them with a set of common underlying assumptions.

(3) Selection from a small series of (3 to 10) prespecified forms in which the characteristics might be related. Visualized here are "black box" or "plug-in" relationships from which the estimator would choose the one which most closely approximates his view of the potential real world situation.

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[*] It should be noted though that more aggregative projections frequently can be prepared which summarize individual projections and encompass a series of successive modes. Obviously definitional and classification considerations also are involved in the question of how great the design change must be to constitute a change in mode.

(4) Plotting the specific relationships among each set of characteristics as best they can be determined.

Approach (3) might be partially accomplished through the use of a simple weighting scheme. For example, if three major variables are involved, reasonable combinations of weights might be:

Characteristic

	1	2	3
Weight	1	1	1
	1	1	2
	1	1	3
	1	2	2
	1	2	3
	1	3	3
	2	3	3

This assumes that if any one characteristic is more than three times as important as the others, then it probably should be considered as dominating, and therefore might be used alone to project potential progress.

A complicating, but not insurmountable, consideration would be the circumstance requiring that differing weights for various portions of the range of technical progress be plotted.

IN CONCLUSION

Consensus techniques have been the subject of considerable intellectual activity recently. When such suggestions for improving the coordination of estimates prepared by various experts are taken together with the several ways provided in this paper for increasing explicitness in basic technological projections hopefully improved technological forecasts will be the result. If a comprehensive methodology incorporating these features can be implemented, then more realistic scheduling of innovations may become a reality. Even more optimistically, perhaps better understanding of the technological component of the lead-time phenomenon will result in better ways of reducing its constituent parts and shorter lead-times actually will be achieved.