A Delphi Technology Forecasting Approach Using a Semi-Markov Concept

YUN YEONG CHO, GI HO JEONG, and SOUNG HIE KIM

ABSTRACT

This paper suggests a technology forecasting approach based on a semi-Markov model, which appropriately describes the probabilistic nature of a sequential technology development process. This approach focuses primarily on the utilization of the information that has been skipped in conventional Delphi survey data. That is, through a simple statistic, the interrelationships among sequential technology developments can be extracted in a formal structure of a semi-Markov model from the original Delphi panel's estimates. A simulation technique is developed to forecast the development process by utilizing the information on such interrelationships. This technique provides a flexible and useful tool for R&D planners or project managers, especially in postanalysis of Delphi forecasting. To make good use of the approach, a computer-based interactive Delphi data analysis system (IDEAS) is implemented in IBM PC.

Introduction

The role of technological forecasting is to aid technology development management in peering into the future. Because R&D planning toward an uncertain future is very difficult and risky, many technological forecasting tools have been developed to alleviate the risk and to obtain more accurate or reliable information.

The history of technological forecasting dates back almost to the Industrial Revolution. One of the battery of technological forecasting tools is the well-known Delphi survey technique that has been applied to a wide variety of problems [1–3]. Although this technique is not a strict forecasting method, it is one that has been found quite useful for technological or qualitative forecasting, especially in long-range forecasting with low information environments.

In the conventional Delphi technique applied to technological forecasting, panelists are asked for their subjective estimates for uncertain future technological events (referred to here as development) in regard to the likelihood of their occurrence, their probable date, desirability, and the like. A summary of the panelists’ estimates in the final round is accepted as a forecast by the panel.

Though many experimental studies verify the accuracy and credibility of the Delphi
technique, from the user’s point of view (such as R&D planners and project managers), the conventional Delphi technique applied to forecasting of closely related future technology developments has a major shortcoming; namely, it does not consider the significance of relationships and interactions between developments. Because of this deficiency, a majority of R&D planners use the Delphi method in conjunction with other formal methods, as has been reported by Brockhaus and Mickelsen [4].

One of the popular Delphi tools used in support of the Delphi technique is the cross-impact analysis [5, 6]. This analysis is explicitly concerned with the complex interrelationships among the various potential future development forecasts. It is based on the evident phenomenon that development of one technology affects the likelihood that other forthcoming technologies will develop. So, in actual application, the Delphi method is commonly combined with cross-impact analysis as in the INTERAX and DELPAC systems, which are interactive software designed to support the Delphi technique [7–10].

Although cross-impact analysis is favored for using Delphi forecasting, it requires information about the interrelationships that is usually represented by a cross-impact matrix. Each element in the matrix is the conditional probability of a certain technology development given another development. Though it could be obtained through other Delphi questionnaires or a panel’s subjective assessments, it would be not only an additional burden but also difficult to obtain because of its complexity and magnification.

This study, following the line of cross-impact analysis, is also concerned with the interrelationships among technology developments, but seeks to avoid imposing any additional burden on panelists or analysts. Instead, it utilizes the information apparently skipped in the original Delphi survey data by adopting a semi-Markov concept [11]. A semi-Markov process may be loosely defined as a stochastic sequential process that transits states in accordance with a given set of probability laws, but takes a random amount of time between the transitions.

The semi-Markov model describes well the sequential technology development process in a specific field of technology having uncertainty. This model characterizes the sequential technology development process by capturing its two probabilistic characteristics, namely, the uncertain sequence of developments and the uncertain time length between successive developments. These two probabilistic natures of the technological process can be formally represented by the state transition and the state holding time concepts in a semi-Markov process. This semi-Markov model can be generalized to any process of interrelated multiple technology development, however, if the Markov property (i.e., that the evolution of the process depends on the state occupied) is assumed. Because the embedded Markov property might be realistically assumed in case of sequential developments having strong interdependence, this study confines the model to this case.

Incidentally, when panelists are asked to predict occurrence times of multiple sequential technology developments in a specific field, before they give the response for each development, it is natural for them to give implicit consideration to the interrelationship of developments based on their subjective belief.

Thus a simple method based on a frequentist approach is developed to extract the information concerning interrelationships from the original Delphi data. That is, the relative frequency of the panel’s subjective judgments about the sequence of the developments and the time span between successive developments can be readily described as probabilistic functional forms of a semi-Markov process. Additionally, in order to combine the information provided by the differing degrees of expertise of the Delphi panel, a new weighting method based on the theory of probability pooling or expert resolution is devised
[12, 13]. Though some researchers [14] have cast doubt on its worth, the weighting for different expertise is generally employed in the aggregation of the Delphi panel’s opinions.

A simulation technique is developed to forecast the development process by utilizing the information on interrelationships. This technique provides a flexible and useful post-analysis tool for R&D planners or project managers to give insights about the development process as a whole. It is useful, especially in sensitivity analysis and policy analysis of forecasting under various assumptions regarding the occurrence or nonoccurrence of a specific technology development, time interval between developments, and specific R&D policy.

To make good use of the approach with easy access to a vast amount of data, a computer-based interactive Delphi data analysis system (IDEAS) is developed. This is a decision support system for R&D planners to implement Delphi forecasting and post-analysis. An example based on a sample of real survey data is introduced with various simulation results.

A Technology Forecasting Method with a Semi-Markov Concept

This study focuses on a Delphi survey applied to sequential technology developments having strong interdependence. A panel of experts predicts the occurrence times of developments as a point estimation based on their beliefs. It is assumed that before each expert gives a response for each prediction, implicit consideration will be given to the interrelationship between developments. Our concern focuses on the data from the final round of the survey. Though some degree of consensus has been arrived at through successive rounds, it is not usually unanimous. In accordance with a frequentist view of probability, the aggregated opinion of the panel is represented by a probability distribution.

In this section, a methodology is developed with the aim of extracting the information concerning the interrelationships between developments from the original Delphi data. To represent the interrelationships in a structured manner, a semi-Markov concept is adopted. A simulation process is generated to provide insights into the behavior of the technology development process.

A SEMI-MARKOV MODEL FOR A SEQUENTIAL TECHNOLOGY DEVELOPMENT PROCESS

In a field of technology, multiple potential developments will occur sequentially over time. The main concern is when the developments occur within a forecasting horizon. To forecast the occurrence times of the multiple developments, a model capturing the sequential interrelationships among them is required.

Suppose that a finite number of potential developments is considered. If a development has occurred at any time, then another advanced development will have occurred after some time interval. Next, another enlargement will follow it in the time horizon concerned. What is uncertain, however, is not only the next advanced technology to be developed but also the time span between developments.

For example, the occurrence of the following four developments in the field of information and communication is concerned with the time interval from 1988 to 2007: development of custom VLSI in Korea (denoted as “a”), development of 64 M DRAM in Korea (“b”), development of 1 G RAM anywhere in the world (“c”), development of a parallel-processing computer in Korea (“d”). These developments are closely related to each other; for example, developments “b” and “d” will occur after “a,” occurrence (or nonoccurrence) of developments “a,” “b,” and “c” would expedite (or delay) the occurrence of “d,” etc. However, there are many scenarios for the sequence of developments and innumerable ones regarding occurrence time. That is, though there exists a
sequential interdependence, the occurrence sequence of developments and the length of
time between them are uncertain. Moreover, the possibility of each development is
certain.

This probabilistic process of sequential technology development can be represented
as a formal stochastic process by adoption of the semi-Markov concept. The semi-Markov
process can be defined as a process whose successive state occupancies are governed by
transition probabilities, but whose stay in any state is described by a random variable
that depends on the state presently occupied and on the state to which the next transition
will be made.

Through simple definition, the technological development process can be described
as a semi-Markov process; i.e., the “development” of a technological process is defined
as the “state” of a semi-Markov process. Then the “state transition” in the semi-Markov
process can be explained as the “occurrence of next development” in the technological
process and, similarly, “state holding time” as the “time length between successive
developments.”

To make the use of the model clear, a Delphi inquiry is illustrated. Suppose that
the Delphi panelists consider the four developments mentioned above. It would be natural
for panelists to predict the occurrence times of each of the four developments by evaluating
implicitly their technological difficulty, the trend of research, their interrelationships, and
other factors. Through the evaluation each expert arrives at his or her own belief about
the sequence of developments and the time length between them. For example, suppose
that an expert predicts the occurrence years of four developments, as shown in Figure 1.
The diagram depicts the expert’s belief about the process of technology development:
Development “a” will occur two years from now. Then, development “b” will occur with
a three-year time lag after the occurrence of “a,” and so on. In terms of a semi-Markov
model, it can be described as follows: The process will first enter state “a” and next will
transit to state “b” after three years of holding time, and so forth. It will be noticed that
the occurrence of development “b” depends on development “a” and that the time interval
depends both on “a” and “b.” That is, in the sequential technological development process,
it can be said that the next development (state transition) depends on the current devel-
lopment (state occupied immediately). Similarly, the time interval between two successive
developments (state holding time) depends on the current development and the one
following (starting state and destination state).

Generally in a Delphi survey, the predictions of the panelists are not in agreement
with each other because the process is uncertain. So the process can be represented by
a stochastic structure in a semi-Markov process.

A semi-Markov process is characterized by the two parameters that determine the
stochastic structure, i.e., state transition probability $p_{ij}$ and holding time probability mass
function $h_{ij}(t)$ where

$$p_{ij}: \text{transition probability that entered state } i \text{ on its last transition will enter state } j
\text{ on its next transition}$$
A DELPHI APPROACH USING A SEMI-MARKOV CONCEPT

\[ h_{ij}(t) \]: holding time probability mass function for a transition from state \( i \) to state \( j \), where \( i, j \) are states and \( t \) is the length of holding time

To model the technology development process as a semi-Markov process, some careful modifications are required. The first one is the addition of dummy states. To incorporate the state of initial time and the possibility that no additional development will occur within the time horizon, a dummy initial state (now) and a final state (final time of planning horizon) are introduced. Another modification is required in view of the real situation that each technology development occurs only once in the planning horizon. That is, in view of the semi-Markov process, once the state has moved out of a particular state, it will never return to the past state. This requires the modification of the Markov parameters after each occurrence of development. This is, however, easily achieved by including a control step in the simulation algorithm to be introduced in the following section, instead of recalculating the parameters.

EXTRACTION OF STOCHASTIC STRUCTURE FROM ORIGINAL DELPHI DATA

For a panelist or analyst, it is difficult to assign accurately the probability of any development occurrence within the given future time interval or, likewise, the probabilistic interrelationships between developments; e.g., the cross-impact matrix. Similarly, the stochastic structure in a semi-Markov model composed with \( p_{ij} \) and \( h_{ij}(t) \) is really difficult to obtain directly from experts.

In order to alleviate the difficulty, a new approach to extract the information from the original Delphi data is necessary. In the frequentist view, the occurrence probability of an event is the frequency based on a large number of experiments. When the Delphi method is applied to technology forecasting, a large number of experts are combined in the survey. Thus it gives the information of probabilistic interrelationships. Figure 2 shows one example of a questionnaire in a Delphi survey.

In this method the stochastic parameters are estimated by simply calculating the relative frequency of the response from the original data. First, define the following terms:

- \( T \): forecasting horizon
- \( i, j \): meaningful technology developments, 0 represents dummy initial state and \( F \) represents dummy final state
- \( n_{ij} \): frequency of responses stating that development \( i \) is followed by development \( j \), i.e., transition from \( i \) to \( j \)
- \( n_{ij}(t) \): frequency of responses stating that the transition from \( i \) to \( j \) takes \( t \) years

Using the above definitions, the transition probabilities from given development \( i \) to each \( j, p_{ij} \), are obtained as follows:

\[ p_{ij} = \frac{n_{ij}}{\sum_{j} n_{ij}} \quad \text{for} \quad j = 0, ..., F \]

The \( p_{ij} \) corresponds, in the frequentist view, to the relative frequency of responses stating the next development will be \( j \), under the condition that development \( i \) has just occurred. These \( p_{ij} \) constitute the transition probability matrix, i.e., the Markov transition matrix. Each row of the matrix represents a conditional probability density function that the process, starting state \( i \), will transit to each state \( j \).
Please write down the year the following development (technology) will take place, evaluate the importance of the development and check the degree of your expertise.

<table>
<thead>
<tr>
<th>Expert NO :</th>
<th>Degree of expertise : high (v) low ( )</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Development</th>
<th>Occurrence time</th>
<th>Importance</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. custom VLSI is developed in Korea</td>
<td>1990</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>b. 64 M DRAM is developed in Korea</td>
<td>1993</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>c. 1 G RAM is developed in the world</td>
<td>1995</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>d. parallel processing computer is developed in Korea</td>
<td>1999</td>
<td>v</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Typical questionnaire format and responses.

Similarly, the holding time probability mass function $h_{ij}(t)$ for given $i$ and $j$ is determined as

$$h_{ij}(t) = n_{ij}(t)/n_{ij} \quad \text{for } t = 0, 1, \ldots , T$$

The computation procedure may be demonstrated through a simple example. Suppose that developments “a” and “b” are involved within a forecasting horizon of seven years. Ten panelists in a Delphi survey have stated their predictions of occurrence times for “a” and “b,” as summarized in Table 1. The occurrence times indicate the years counted from now. The “non” denotes the nonoccurrence of a development within the forecasting horizon.

From Table 1, the frequency of responses, $n_{ij}$, and the transition probability, $p_{ij}$, are obtained as the following matrix representations of Table 2. As an illustration, the

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Delphi Survey Data of Occurrence Times of Developments “a” and “b”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expert no.</td>
<td>1</td>
</tr>
<tr>
<td>Development “a”</td>
<td>2</td>
</tr>
<tr>
<td>Development “b”</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>Frequency Table and Transition Probability Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>From \ To</td>
<td>0</td>
</tr>
<tr>
<td>Frequency $N_{ij}$</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>“a”</td>
<td>0</td>
</tr>
<tr>
<td>“b”</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>Transition probability $p_{ij}$</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>“a”</td>
<td>0</td>
</tr>
<tr>
<td>“b”</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
</tr>
</tbody>
</table>
A DELPHI APPROACH USING A SEMI-MARKOV CONCEPT

TABLE 3

<table>
<thead>
<tr>
<th>(i,j)</th>
<th>t</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<tbody>
<tr>
<td>(0,&quot;a&quot;)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>1/5</td>
<td>2/5</td>
<td>1/5</td>
<td>1/5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(0,&quot;b&quot;)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1/4</td>
<td>2/4</td>
<td>1/4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(&quot;a&quot;,&quot;b&quot;)</td>
<td></td>
<td>0</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(&quot;b&quot;,&quot;a&quot;)</td>
<td></td>
<td>0</td>
<td>2/3</td>
<td>1/3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The holding time probability density function, \( h_i(t) \), is computed by dividing each frequency \( n_{ij} \) by \( n_i \). The holding time density function, \( h_i(t) \), is obtained as in Table 3. The figure of the table is represented by a fractional number. The numerator and denominator are the defined frequencies of responses, \( n_i(t) \) and \( n_{ij} \), respectively.

Additionally, in order to combine the information on different expertise degrees of two panelist groups (one having greater expertise and another having less expertise, denoted by group A and group B, respectively), a weighting method based on the sample variance is devised. The predictions of occurrence time of a development from group A usually show smaller deviation among one another than those of group B. This phenomenon can be interpreted by the consideration that a panelist having greater expertise about the relevant technology would predict the occurrence time more accurately than one having less expertise. Thus, in combining data groups, the sample variance can be used as an proxy measure of the cardinal degree of expertise, i.e., the weight assigned to each group.

This method is based on the central limit theorem that a sample mean has an approximate normal distribution and the variance of the sample mean decreases as the sample size increases. Suppose \( \bar{x}_1, \bar{x}_2, \ldots, \bar{x}_n \) and \( \bar{y}_1, \bar{y}_2, \ldots, \bar{y}_m \) are two data groups of sample mean, from same population with mean \( \mu \) and variance \( \sigma^2 \), having different sample sizes \( n_A \) and \( n_B \), respectively. Then, \( \bar{x}_i \) and \( \bar{y}_i \) have normal distributions having equal mean \( \mu \), but different variances, \( \sigma^2/n_A \) and \( \sigma^2/n_B \), respectively. The sample variance of data group A, \( s_A^2 = \frac{1}{n_A-1} \sum (x_i - \bar{x})^2 \), is an unbiased estimate of \( \sigma^2/n_A \). Similarly, \( s_B^2 \) is the unbiased estimated of \( \sigma^2/n_B \). Thus the equation of \( \hat{\sigma}^2 = s_A^2/m_A = s_B^2/m_B \) is derived. A weighting concept can be applied to aggregation of two data groups, using the ratio of the sample variances. That is, \( \bar{x}_i \) has as much worth as \( s_B^2/s_A^2 \) times that of \( \bar{y}_i \).

In this study, the weights for different expertise groups A and B are assigned as \( w_A \) and \( w_B \) where \( w_A = \frac{s_B}{\sqrt{s_B \cdot n_A + s_A \cdot n_B}} \) and \( w_B = \frac{s_A}{\sqrt{s_A \cdot n_B + s_B \cdot n_B}} \). Here \( n_A, n_B \) are number of panelists in two groups and \( s_A, s_B \) are average sample variances of predictions on each developments of groups, respectively. The stochastic structure of the semi-Markov is reestimated by combining the estimates of two groups with their weights.

For example, suppose that the data of Table 1 have come from group A. Then, \( n_A \) is 10. Disregarding the “non” prediction, the sample variances of development “a” and “b” are 2.23 and 1.23, respectively. The average sample variance, \( s_A \), is 1.73. On the other side, suppose that data group B is composed of 30 experts, i.e., \( n_B = 30 \), show 2.60 as the average sample variance, \( s_B \). Then the weights \( w_A \) and \( w_B \) are obtained as 0.4 and 0.6, respectively. For example, suppose that the transition probabilities \( p_{00} \) from two groups, denoted \( p_{00}^A \) and \( p_{00}^B \), are 0.5 ( = 5/10) and 0.2 ( = 6/30), respectively. Then the combined probability \( p_{00}^C \) with weight is 0.32. This result is closer to the estimate of group A than one obtained by simple combining without the consideration of expertise, where the combined probability is 0.275 ( = 11/40 = (5 + 6)/(10 + 40)).
A FORECASTING METHOD BASED ON SIMULATION

The simulation technique is not a strict forecasting method, but it derives new estimates utilizing the prior stochastic structure that is abstracted from the original Delphi data. The estimates can be regarded as representative of the sequential technology development process, taking the interrelationships into consideration. That is, not only are the panelists’ predictions of the individual technology developments considered but also the interrelationships between developments.

The major goal of this simulation is not the recovery of the original forecasts but mainly the sensitivity and policy analysis for the forecasts. That is, this method has the aim to utilize the original stochastic structure of the Delphi survey data as a basis of post-analysis.

Furthermore, this model, using a semi-Markov concept, has more flexibility than a general cross-impact analysis, because of the ease of handling the holding time mass function relating the time interval between successive developments.

This simulation is implemented, as usual, by using the Monte Carlo event generation method based on the semi-Markov concept. As a result, the cumulative occurrence probabilities of each development over time are obtained and analyzed. Of course, these probabilities are estimated by their frequencies.

The simulation procedure run follows the steps diagrammed in Figure 3, given the initial \( p_{ij} \) and \( h_{ij}(t) \):

1. Determine iteration number and set up conditions.
2. Choose next destination state \( j \) from current \( i \) by using transition probabilities \( p_{ij} \) for \( j = 0, \ldots, F \). If the state occurred already, regenerate next state.
3. Select the holding time \( t \) between current and destination states from \( h_{ij}(t) \) for \( t = 0, 1, 2, \ldots, T \).
4. Determine the transition state and its holding time and reset the current state and time.
5. If the current time is greater than the planning horizon or if the dummy final state is selected, then one forecasting run is finished. Otherwise go to step 2.

In a simulation, steps 1 through 5 repeat over a large number of runs. The regeneration control in step 2 actually takes the place of revision of the transition probabilities, as mentioned in the previous section. This reflects the fact that one development occurs at most once in the forecast, by a simple control. Figure 4 depicts a simulation run in the simple case of two developments, using the chains of semi-Markov process. Because each run is, conceptually, equivalent to one expert’s judgment in a Delphi survey, the run number can be fitted to the original sample size of the data. Thus it will ensure the same statistical significance as the original Delphi data. The simulation run, however, can be repeated many times beyond the original sample size without the cost and time burden involved in an actual Delphi survey. After all runs, all frequency of occurrence of each development over time determines the probability of its occurrence at each time.

A Computer-Based Delphi Supporting System

INTERACTIVE DELPHI DATA ANALYSIS SYSTEM (IDEAS)

Based on the methodology in the previous section, a computer-based interactive Delphi data analysis system (IDEAS) is developed. This is a decision support system for
R&D planners to implement Delphi forecasts and post-analysis with easy access to a vast amount of data. It is implemented on IBM PC environment allowing easy access.

The basic four functions of this system are as follows: data analysis, simulation, sensitivity and policy analysis, and reporting. Data analysis and simulation function include the gathering of the Delphi response data, estimations of the holding time probabilities and transition probabilities for initializing the run, and simulation.

The sensitivity and policy analysis functions constitute the main strength of this system. Sensitivity analysis means testing of the forecasts under the different conditions regarding the stochastic structure of the original Delphi data. It consists of modification of a particular holding time probability or transition probability regarding the developments of interest and weighting factors for expertise. Policy analysis is accomplished to test the forecasts of the development process under different conditions regarding anticipated
policies or actions. These include occurrence (or nonoccurrence) of a specific development or assignment of development duration and sequence. It also requires some modification of the stochastic structure similar to sensitivity analysis. A new run is then performed and the results are compared with the original Delphi estimations.

The reporting function generates various outputs. These include a frequency table, a probability function for each development occurrence, by any time instant or over the entire span of the time interval, and, additionally, holding time probabilities and transition probabilities for all events. Graphical displays are also suggested to understand this information easily.

The application program written in BASICA is divided into several modulized programs. The system architecture is portrayed in Figure 5. Though this system is limited by the size of PC memory, it will be helpful where R&D planners are engaged in analyzing a moderate number of technology development forecasts (in practice, up to 20 developments). By using a hard disk or fixed drive, a vast amount of original Delphi data can be filed and analyzed.

AN EXAMPLE AND ITS POSTANALYSIS

The use of IDEAS system is demonstrated by a simple example of three developments, taken from actual Delphi data. The Delphi survey was carried out by the Korean Research Center of Science and Technology Policy, under the research program of "Long-range Technology Forecasting in Korea." This survey covered a wide range of potential technological developments, including 359 developments in the nine main categories of technological fields, which bear both on Korea and the world. A total of 1110 experts joined in this survey over two years from 1986 to 1987.

The three developments of this example (denoted by "a," "b," and "c") were sampled from the semiconductor field of the survey. The contents of these developments have been described by same denotations as in Figure 2.

Using the data analysis function of IDEAS, the stochastic structure of the process, i.e., the transition probability matrix and holding time mass function, is generated. Figure 6 shows the transition probability matrix. Figures of the data can be interpreted as follows: 74% of the panel believe that the first realization of these three developments will be "a"
(development of custom VLSI in Korea); 65% of them believe that “b” (development of 64 M DRAM in Korea) will follow “a”; 3% of them believe that neither “b” nor “c” will follow “a,” and so forth. Figure 7 illustrates the holding time mass function. It depicts the probability mass function of time length between “a” and 0 (dummy initial starting state), $h_{0a}(t)$. It indicates the following: 12% of the panel’s responses state that “a” will occur after one year from now; 27% of them state the duration will be two years; and so forth. It also shows, however, the existence of severe disagreement among the panelists’ opinions.

Using the stochastic structure, the occurrence times of each development have been

<table>
<thead>
<tr>
<th>Transition Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>a</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>c</td>
</tr>
<tr>
<td>F</td>
</tr>
</tbody>
</table>

Fig. 5. Overview of system (IDEAS).

Fig. 6. Transition probability matrix of the example.
forecasted through a simulation run. Figure 8 shows the cumulative probabilities of original Delphi data and results of simulation in comparison. Ignoring some minor differences, it shows the close similarity between both occurrence probabilities.

Now, we will describe how the post-analysis procedure operates in this system. There are three possible actions: the weighted information for each group, the holding time mass functions, and the transition probabilities between developments may be adjusted by subjective assignments. These types of modification could cover any possible sensitivity and policy analysis.

First, this approach suggests a weighting based on the variance technique, or an inquiry into the subjective weight for each expertise group. The following shows the query of the system:
After change

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>F</th>
</tr>
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Fig. 9. Revised holding time mass function and transition probability matrix.

The system suggests the following weighting:
- 0.73 for group A (greater expertise)
- 0.27 for group B (less expertise)

If you want to change the weighting,
then how much weight for group A?
for group B?

This assignment (weighting 1 for group A and 0 for group B) can be interpreted as indicating that the user disregards the information from panelists who have less expertise. Using the revised weighting, a new run is performed. Although the simulation results are not illustrated here, it can be noticed that group A (whose members have greater expertise for each development) has a more optimistic view of the occurrence of developments, especially for development "b."

Second, to illustrate the modification of holding time mass function, suppose that it will take exactly three years for the realization of "a" from the initial starting point. Then the holding time probability mass should be assigned as $h_{0a}(3) = 1$, $h_{0a}(t) = 0$ for all $t \neq 3$. After the modification, the system displays the probability function as in Figure 9. Using the revised probability mass function, similarly, a new run can be performed.

And finally, for the sensitivity of the transition probability matrix, suppose that developments "a," "b," and "c" occur with the corresponding sequence. This condition is equivalent to one that the transition probabilities $P_{aa}$, $P_{ab}$, $P_{bc}$, and $P_{cf}$ are 1 and all other elements in the matrix are 0. It is also depicted in Figure 9. The simulation result with these three types of modifications is shown in Figure 10.

Through this example it has been described how the model would be used and how the sensitivity or policy could be tested. Actually, this model has provided a useful analysis of technology forecasting.

Conclusions

This study presented a new technology forecasting approach based on the semi-Markov concept. The proposed method of forecasting is simple and practical in its application to the case of sequential technology development process.

This model has been implemented efficiently on a personal computer with easy access to a vast amount of data. It will be helpful for R&D planners or project managers in the post-analysis of Delphi forecasts.

The semi-Markov concept, giving an adequate description of the real-world envi-
environment of technology forecasts, will provide, as designed, the possibility of using unrevealed information in a Delphi survey. The frequentist approach and weighting concept used are simple to employ.

As a further extension, it would be meaningful to combine this system with other decision-making models of R&D planning or project management.

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References


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