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AN ANALYTICAL APPROACH TO BUILDING A TECHNOLOGY DEVELOPMENT ENVELOPE (TDE) FOR ROADMAPPING OF EMERGING TECHNOLOGIES

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This paper presents the research on the development of a new concept and methodology called Technology Development Envelope (TDE). The TDE approach is applied to identify the optimum path in developing a technology roadmap in which the company's technology strategies and business strategies are combined. TDE allows the executive level decision makers in corporations, as well as the policy level decision makers in governments to incorporate emerging technologies into the development of technology strategies. The combination of Delphi method and Hierarchical Decision Modeling (HDM) is used as a foundation for building the TDE concept. The judgments from technology developers and technology implementers are utilized in the process to ensure that the technology strategies are in full support of corporate goals and objectives.

Keywords: Technology development envelope; TDE; technology roadmapping.

1. Introduction

In order to survive in today's fast changing business environment and intense market competition, technology-based companies look for R&D investment in emerging technologies as a key solution [Schmitt (1985); Sugiura (1990); Radhakrishna and Vardarajan (1991); Kokubo (1992); Betz (1998)]. Successful implementation of technologies can strongly enhance a company's competitiveness. However, due to funding constraints, companies must cautiously evaluate technologies before they invest.

An analytical model was developed in this research to help managers understand how technologies are evolving and how well different technologies fit their corporate strategy. The model combines technology forecasting, identification, assessment, evaluation, and selection.

The Delphi method for obtaining expert opinion is applied to generate strategic information regarding potential emerging technologies including their estimated introduction date and their characteristics.

Emerging technologies are then evaluated using a hierarchical decision model with four levels: objective, criteria, factors, and technology alternatives. Comparative judgments provided by experts are analyzed to determine the relative priorities of the components in each level of the hierarchy. A new method for applying a semi-absolute scale to quantify the value of each technology is proposed. The overall impact of each technology on the company's strategic objective is calculated as a composite index called Technology Value.

Technology development paths are specified by connecting technologies from one period to the next. The path connecting technologies with the highest value in each time period is defined as the "technology development envelope (TDE)." By investing in technologies following the TDE path, a company's technological benefits will be maximized. The TDE and the various technology development paths serve as strategic inputs to the company's technology roadmapping process.

Determining the value of emerging technologies with respect to a company's strategic objective is a valuable process in its own right. However, the results of this research go beyond that. They show that the proposed method leads to a technology development envelope and suggestions for possible technology development paths where none had existed previously. This method was developed using a systematic approach, and was subjected to various tests to show that the method is robust with respect to the variations in the company's priorities.

To demonstrate the process, a specific case study is presented for the development of a TDE on emerging electronic cooling technologies for one of the leading computer server developers. Currently, this industry is in a technological transition period due to the volumetric thermal density limitation of the current electronic cooling technology — direct air cooling.

2. Literature Review

To lay out a fundamental understanding of this research, an extensive literature search was conducted on topics including emerging/disruptive technologies, technology forecasting, Delphi method, technology identification, technology assessment, technology evaluation, technology selection, analytical hierarchy process (AHP), and technology roadmapping. The major emphases and potential gaps in the existing literatures are summarized below:

- A wide range of research is available on technology forecasting and assessment methods such as statistical technology forecasting, trend analysis, and judgmental methods [Jantsch (1967); Cetron (1969); Bright and Schoeman (1973); Mitchell (1975); Twiss (1976); Martino (1987); Porter (1991)]. Yet, there is a limited number of studies combining expert opinions and analytical models for forecasting the impact of technologies on corporate objective [Dalkey and Helmer (1963); Hill and Fowler (1975); Linstone and Turoff (1975); Dieftz (1987); Van Dijk (1990); Shin (1998); Rowe and Wright (1999)].

- Most of technology forecasting applications are applied to the extension of existing technologies, not emerging technologies [Martino (1993); Bower and Christensen (1995); Cauffiel and Porter (1996); Watts and Porter (1997); Chakravarti *et al.* (1998); Linstone (1999)].
- Despite an abundance of literature on decision–support models and applications for identifying or selecting technologies, only a few studies specifically address emerging technologies. The development of a decision-support model for emerging technology applications tends to be more sophisticated than the ones for existing technologies. This results from the fact that not only both quantitative and qualitative measures must be taken into consideration, but also the limitation on historical data availability of emerging technology has to be overcome [Hall and Nauda (1990); Iyigun (1993); Chun (1994); Kocaoglu and Iyigun (1994); Henriksen and Traynor (1999); Stummer and Heidenberger (2001)].
- Generally, decisions for technology evaluation are exclusively made by a group of technology managers in companies. It is rare that decisions are made in the environment which technology developers and technology implementers interactively participate [Souder (1975); Saaty (1980); Costello (1983); Liberatore and Titus (1983); Linstone (1999); Easley *et al.* (2000)].
- Although the use of technology roadmaps as a technology forecasting technique is spreading among industries, a systematic approach for building a roadmap and keeping it alive is not well defined in the literature [Willyard and McClees (1987); Galvin (1998); Gedney *et al.* (1998); Radnor and Peterson (1999); Kostoff and Schaller (2001); Shaller (2001)].
- Technology roadmapping processes are carried out either internally within a company or externally among peer technology developers across industries. The linkage between external researchers/developers and corporate decision makers in roadmapping is weak [Bray and Garcia (1997); Groenveld (1997); Kappel (2001); Phaal and Probert (2001)].
- Strategic management of technology is practiced by applying tools, concepts, and processes in different companies. Therefore, there is an opportunity to develop an operationalizable model to guide the entire process.

3. Research Objective, Goals and Questions

The objective of this research was to develop an analytical approach to build a strategic technology development envelope (TDE) for roadmapping of emerging technologies. The approach involves forecasting, identification, assessment, evaluation, and selection of emerging technologies. The combination of the Delphi method and hierarchical decision modeling is applied in this research [Khorramshahgol *et al.* (1988); Khorramshahgol and Steiner (1988); Khorramshahgol (1988); Azani and Khorramshahgol (1992); McCarthy (1992); Tavana *et al.* (1993); Byun *et al.* (1998)].

The research objective was achieved by fulfilling five research goals. One or more research questions needed to be answered for each goal. The research goals and questions are summarized in Table 1.

Table 1. Research goals and research questions.

Research goals	Research questions
RG1: Develop a forecasting model using Delphi for identifying the trends of emerging technologies.	RQ1: What is the trend of emerging technology development in the industry?
RG2: Develop a judgment quantification model for evaluating the value of emerging technologies on a company's objective.	RQ2: What are the significant criteria and technological factors associated with each criterion to satisfy the objective? What should be the measures of effectiveness applied for each factor?
	RQ3: What is the relative priority of each influencing criterion?
	RQ4: What is the relative importance of influencing technological factors on each criterion?
	RQ5: How should the measures of effectiveness be evaluated in terms of their relative desirability for the objective?
RG3: Assess technological characteristics of each emerging technology along the identified factors.	RQ6: How should the characteristics of emerging technologies be assessed based on their technological metrics?
RG4: Evaluate emerging technologies.	RQ7: How should the value of emerging technologies be evaluated in terms of the relative desirability of their technological metrics for the objective?
RG5: Construct the technology development envelope and paths by sequentially connecting one technology to another over time.	RQ8: What is the technology development envelope? How can it be determined? RQ9: How can the possible paths of technology development be identified?

4. Research Approach

The research consisted of six steps: technology forecasting, technology characterization, technology assessment, technology evaluation, hierarchical modeling, and formation of a technology development envelope (TDE) as shown in Fig 1. Each step was designed to accomplish a specific research goal as summarized in Table 1.

Step 1 Technology Forecasting: Develop a forecasting model using Delphi for identifying the trend of emerging technologies. (RQ1)

Step 2 Technology Characterization: Identify criteria and technological factors satisfying a company's objective. (RQ2)

Step 3 Technology Assessment: Assess emerging technologies based on the measures of effectiveness (metrics). (RQ6)

Step 4 Hierarchical Modeling: Develop a hierarchical model to determine the relative importance of criteria, the relative impact of factors under each criterion, and the relative desirability of measures of effectiveness on each factor. (RQ3–5)

Step 5 Technology Evaluation: Evaluate the semi-absolute impact value of emerging technologies on a company's objective. (RQ7)

Step 6 Formation of TDE: Construct the technology development envelope and technology development paths. (RQ8–9)

Due to limited data availability inherent in emerging technologies, and complex issues in combining qualitative and quantitative aspects into decision-making process, it is always challenging for any organization to understand how emerging technologies are evolving over time and how the development of those technologies impacts an organization's objective.

To overcome these challenges, two expert panels, technology developers (EP-1) and technology implementers (EP-2), were formed to provide inputs and complete specific requirements in each process. The flow of strategic information through these six steps as well as the interaction between the two expert panels is shown in Fig. 1.

5. Expert Panels

Each panel is a group of experts who have expertise in a particular area. Members of each expert panel are required to provide balanced representation of ideas/backgrounds and have little or no bias regarding the outcomes of the study. Also, they must be in a position to understand the overall scope of the issues and to influence the decision process. The description and role of each expert panel is described below:

Expert Panel 1 (EP-1) is a group of "technology developers" widely chosen from the industry. This group of experts is *a technology-dependent source of knowledge*. EP-1's responsibilities are to identify a list of emerging technologies with the expected time of their occurrence and to provide the measures of effectiveness of each emerging technology.

Expert Panel 2 (EP-2) is a group of "technology implementers" in an organization who design and develop technologies into products. This group of experts is an organization-dependent source of knowledge. EP-2's responsibilities are to identify

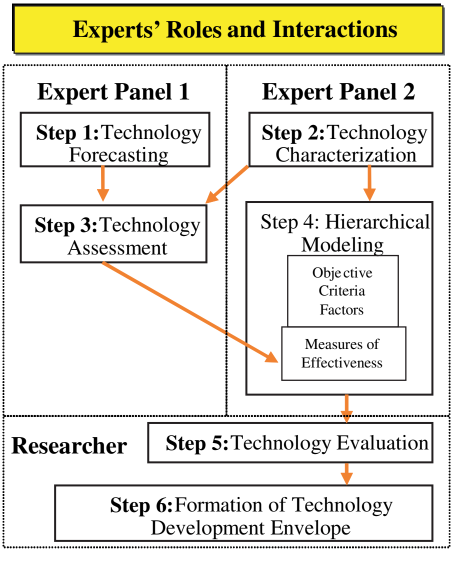


Fig. 1. Six-Step TDE development.

a set of criteria and technological factors associated with each criterion for satisfying the organization's objective of achieving technological competitiveness. They determine the relative importance of criteria, the relative impact of technological factors on each criterion, and the relative desirability of measures of effectiveness on each technological factor.

6. TDE Model Development

The list of potential emerging technologies, the estimated time of their occurrence (resulting from Step 1), and the metrics describing the performance and physical characteristics of each technology (resulting from Step 3) were obtained from the expert group of technology developers through Delphi process. The evaluation model was constructed in a hierarchical format with four levels: objective, criteria, factors, and characteristic metrics as shown in Fig. 2. (resulting from Step 2). The comparative judgments to determine the relative priorities of components at each level of the hierarchy were provided by the expert group of technology implementers (resulting from Step 4). The characteristic metrics of each technology were evaluated according to the organization's judgments on the desirability of each metric, the relative impact of factors associated with each criterion, and the relative priority of criteria on the objective. The computational results of the technology evaluation are presented as a composite value called Technology Value indicating the overall impact of each technology on the company's strategic objective (resulting from Step 5). The mathematical model for the technology evaluation was developed as shown in the next section. A technology evaluated with the highest value in each time period represents the technology for which a company has the highest preference compared with other technologies. The path connecting technologies from one period to another is a technology development path. The path connecting technologies that have the highest value in each time period is defined as the "technology development envelope" as shown in Fig. 3. (resulting from Step 6).

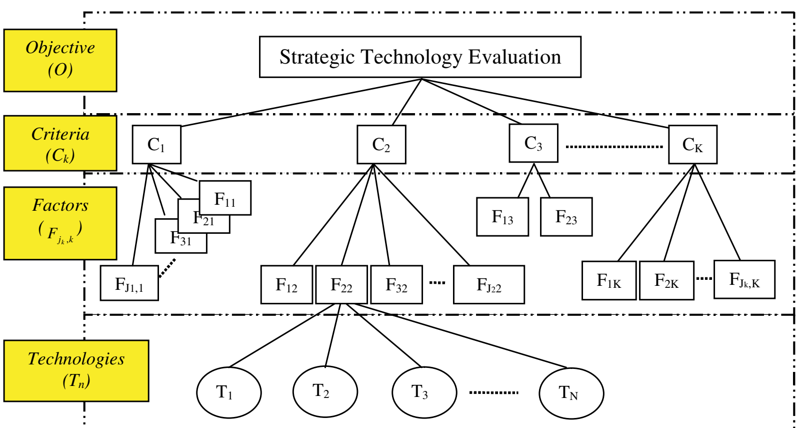


Fig. 2. Hierarchical model for evaluating emerging technologies.

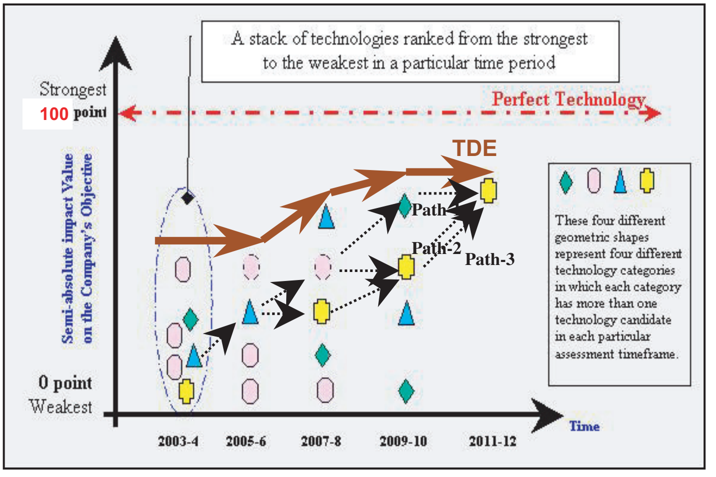


Fig. 3. TDE diagram.

7. Implications of TDE Diagram for Roadmapping

As conceptually defined, the TDE, a path connecting technologies with the highest value over the time periods, is the optimum technology development path for the company to invest. The company should effectively utilize its resources to keep up with the TDE so that its technological benefits will be maximized. In this case, the TDE can be referred as the company's technology roadmap.

In other cases where the company may not be able to effectively mobilize its resources to keep up with the TDE, then the TDE is used as a benchmark for the company's technology roadmap. Other technology development paths (Path-1, Path-2, Path-3, etc.) will be considered along with the company's resource availability to determine the company's most suitable technology roadmap.

8. Mathematical Model

The mathematic model for the evaluation of emerging technologies is shown below,

$$TV_n = \sum_{k=1}^{K} \sum_{j_k=1}^{J_k} w_k \cdot f_{j_k,k} \cdot V(t_{n,j_k,k}), \tag{1}$$

where

- TV_n: Technology value of technology (n) determined according to a company's objective
- w_k: Relative priority of criterion (k) with respect to the company objective
- $f_{j_k,k}$: Relative importance of factor (j_k) with respect to criterion (k)

$\sum_{j_k=1}^{J_k} w_k \cdot f_{j_k,k}$: Relative importance of factor (j_k) with respect to the objective

$t_{n,j_k,k}$: Performance and physical characteristics of technology (n) along with factor (j_k) for criterion (k)

$V(t_{n,j_k,k})$: Desirability value of the performance and physical characteristics of technology (n) along factor (j_k) for criterion (k)

The technology value is calculated through matrix computations among the criteria priorities $[w_k]$, the relative importance of factors on each criterion $[f_{j_k,k}]$, and the desirability of technologies for each factor $[V(t_{n,j_k,k})]$.

This value indicates the level of company's appreciation on the development of any specific technology over time compared with a company's perception of an ideal technology.

9. Research Instruments

The research instruments were specifically designed to capture information about the future development of emerging technologies and the measurement of impacts of technologies on a company's objective. The structure of research instruments facilitates Delphi feedbacks and judgment quantifications as well as the collection of anonymous opinions.

Internet tools were applied as the backbone architecture of all research instruments. This way, the demographic limitations due to the widespread locations of experts in this research were overcome at no cost. In addition, the use of an Internet-based survey alleviated the research participants' time constraints and encouraged them to provide immediate responses.

10. Data Analysis

Data analysis was conducted in three areas: Delphi outputs on technology forecasting and assessment, Judgment quantification for the evaluation of emerging technologies, and Formation of a Technology Development Envelope (TDE).

Delphi Study: the outputs include the list of emerging technologies and the time of their occurrence. Descriptive statistics are applied to analyze the distribution of expert opinions. The stability between successive Delphi rounds is tested to statistically verify when the Delphi study can be stopped. The chi-square test is applied for this purpose to determine whether there is a significant difference between individual responses in different rounds.

Judgment Quantification: The relative priority of the criteria and the relative importance of factors associated with each criterion are determined through a series of comparative judgments provided by each expert. Experts' judgments are expressed by allocating a total of 100 points between two elements at a time (applying the Constant-Sum Method). The judgments are converted to a normalized measure of relative values in ratio scale. The level of agreement among the group of experts is tested to determine the degree to which experts are in agreement with one another according to their judgments. The expert agreement on the judgment values and rankings of elements is measured by Interclass Correlation Coefficient and Kendall's Coefficient of Concordance. F-test and Chi-square test are applied respectively, to statistically verify the significant level of agreement.

Formation of TDE: Technologies are arranged according to their technology value in each time period, the lines serially connecting one technology to another technology in the later time periods represent paths of technology development. The path connecting technologies whose values are highest in each time period is considered the Technology Development Envelope (TDE).

11. Research Validation

Three tests were conducted to validate this research for: content validity, construct validity, and criterion-related validity.

Content validity was tested in the research preparation phase and the development of research instrument to ensure that all information can be captured as intended. Construct validity was tested when the hierarchical decision model was developed to assure unidirectional hierarchical relationships among decision levels, and independence among decision elements. Criterion-related validity was tested after the completion of the model to see how adequately the results represent the reality.

12. Case Study — Determination of TDE on Emerging Electronic Cooling Technologies

The research results were applied to the development of electronic cooling technology, and tested in a leading computer server developer company. The application demonstrated the robustness of the approach and the model. The details are shown below.

Currently, the technological improvement of existing cooling technologies is reaching the volumetric limitation [Azar (2001); Khrustalev (2001)]. This challenge will eventually become a roadblock for electronic industry [Azar (2000); Viswanath *et al.* (2000); Intel (2001); Montgomery *et al.* (2002)]. R&D departments of many institutes in both industry and academia have been working on developing a new cooling technology. Some of new technologies are completely different from the existing ones as the emerging concepts of nano-engineering and power-free are applied. An official technology roadmap representing the future direction of the industry has not been recently presented because the industry is in the technological transition period and many developments of new technologies are still in an infancy stage.

Two expert panels were formed. EP-1 consisted of twelve members representing industry, academia, and government. Their roles and titles ranged from VP, CTO, engineering manager, senior technical staff, research engineer, and professor. EP-2 consisted of eight members from the company representing R&D, technology enabling, technology implementation, assembling and manufacturing department.

12.1. *Step 1 & 3 — Technology forecasting and assessment*

Thirteen emerging electronic cooling technologies were initially identified from the most up-to-date literature and sent to EP-1 experts to estimate their availability for OEM's implementation. Four new emerging technologies were also added by the experts into the initial list after the 1st round of Delphi study. Therefore, the total number of emerging electronic cooling technologies included in this study was seventeen as listed in Table 2.

The group of EP-1 experts agreed that sixteen of seventeen technologies would be ready for implementation by OEM's implementation by 2010. The group agreement on the time of occurrence of each technology is defined as the specific time by which 50% of experts agree that this particular technology will be ready for implementation. The specific time of occurrence of each technology is shown in Fig. 4.

Experts also provided their estimates on the technological metrics indicating the future development progress of each technology along 22 factors.

12.2. *Step 2 & 4 — Technological characterization and hierarchical modeling*

The group of EP-2 experts agreed on defining the objective of their technology evaluation as "to achieve technological competitiveness from new thermal platform

Table 2. List of emerging electronic cooling technologies.

Pre-identified Emerging Technologies			
T1:	Air Cooling	T12:	Thermoelectric Cooling
T2:	Air flow-Through and Cold-Wall Cooling	T13:	Thermo-Tunneling
T3:	Cold Plate Cooling		
T4:	Channel Flow Boiling	*Additional Emerging Technologies*	
T5:	Pool Boiling/Thermosyphons	N1:	Mechanically pumped single-phase liquid cooling
T6:	Jet-impingement and Spray Cooling		
T7:	Immersion-Liquid Cooling	N2:	Mechanically pumped single-phase liquid with heat removal by two-phase heat transfer
T8:	Vapor Compression		
T9:	Phase Change Cooling		
T10:	Heat Pipes	N3:	Electrohydrodynamics
T11:	Capillary Pumped Loops	N4:	Oscillatory heat pipes

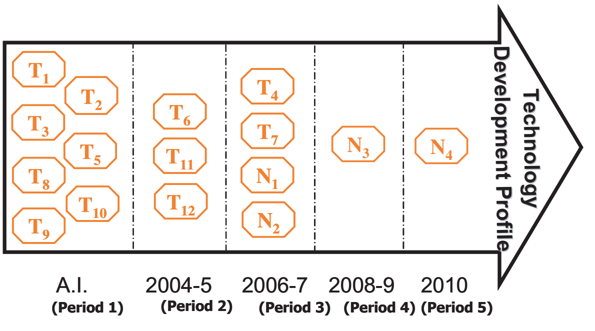


Fig. 4. Representing the specific time of occurrence of each technology.

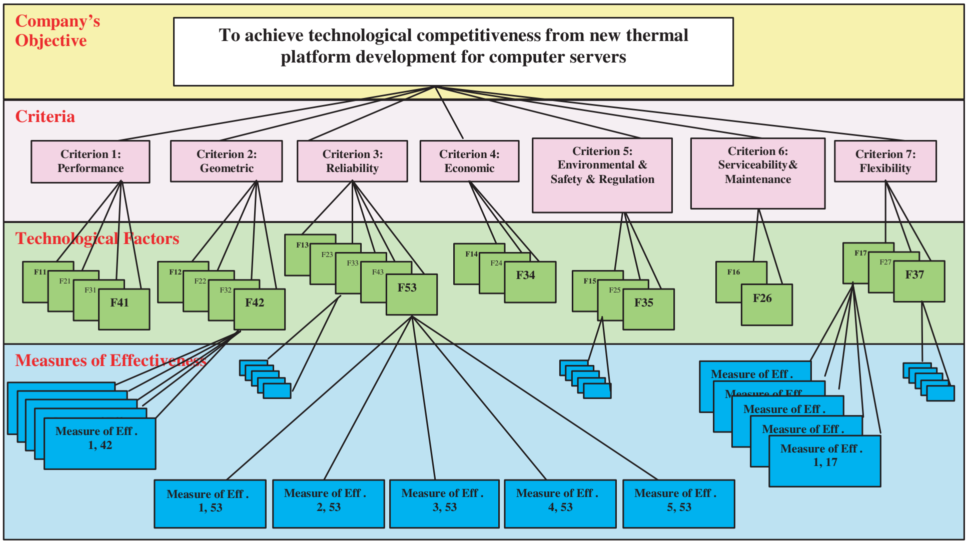


Fig. 5. Hierarchical model for the evaluation of electronic cooling technologies.

development for computer servers". Seven criteria and factors associated with each criterion along with their limiting values on the measure of effectiveness were finalized. The hierarchical model for technology evaluation was structured according to the relationship among the seven criteria and all factors as shown in Fig. 5.

A series of experts' comparative judgments on each pair of criteria and factors were analyzed to determine the relative priority of criteria as well as the relative importance of factors associated with each criterion. The desirability curves representing the company's preference on the technological metrics of each factor were developed.

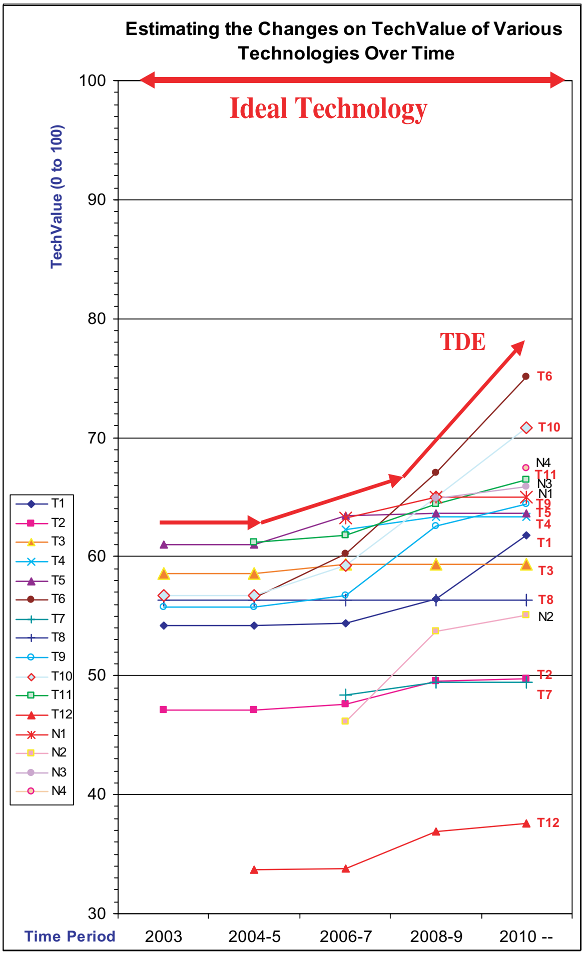
12.3. *Step 5 — Technology evaluation*

Each technology was evaluated in each time period by measuring how well their technological metrics meet the company's desirability level and then factored that by the relative importance of factors and the relative priority of criteria (as described in Mathematical Model section). The graphical results representing technology value of all sixteen technologies over time are shown in Fig. 6.

The analysis results indicate that the technology value of Jet-impingement/ Spray Cooling (T6) would be significantly improved overtime as the development of this technology goes on. And eventually, this technology would become a dominant technology by the end of the decade. The current technology — air cooling — will not be attractive any more even though the production cost will continue dropping.

12.4. *Step 6 — Formation of technology development envelope (TDE)*

From the results, a technology development envelope (TDE) was formed as a path connecting Pool Boiling (T5) in 2003, Capillary Pumped Loops Heat Pipes (T11) in



<u>Notation</u>

$T_{n,i}$: Representing technology n which the time of its occurrence is estimeted to be in i period.

i: 1 (2003); 2 (2004-5); 3 (2006-7); 4 (2008-9); 5 (2010-); 6 (Never)

$T_{1,1}$: Air Cooling
$T_{2,1}$: Air flow-Through and Cold-Wall Cooling
$T_{3,1}$: Cold Plate Cooling
$T_{4,3}$: Channel Flow Boiling
$T_{5,1}$: Pool Boiling/Thermosyphons
$T_{6,2}$: Jet-impingement and Spray Cooling
$T_{7,3}$: Immersion-Liquid Cooling
$T_{8,1}$: Vapor Compression
$T_{9,1}$: Phase Change Cooling
$T_{10,1}$: Heat Pipes
$T_{11,2}$: Capillary Pumped Loops
$T_{12,2}$: Thermoelectric Cooling
$T_{13,6}$: Thermo-Tunneling
$N_{1,3}$: Mechanically pumped single-phase liquid cooling
$N_{2,3}$: Mechanically pumped single-phase liquid with heat removal by two-phase heat transfer
$N_{3,4}$: Electrohydrodynamics
$N_{4,5}$: Oscillatory heat pipes

Fig. 6. Position of technologies ranked by their impact values on a company's objective.

2004–2005, Mechanically Pumped Single-Phase Liquid Cooling (N1) in 2006–2007, and Jet-impingement and Spray Cooling (T6) from 2008–2010. The value of these four technologies is the highest in those periods.

13. Conclusion and Contributions

The main contribution of this research is the enhancement of the Body of Knowledge in strategic planning for development of emerging technologies. The research was a systematic approach for developing a technology development envelope (TDE) by applying the concepts of technology forecasting, evaluation, and selection in conjunction with multi-criteria decision-making methodologies. The technology development envelope (TDE) is a strategic input to technology roadmapping. The decision support model developed in this research fills a challenging gap that technology managers are facing in linking technology development to corporate strategy.

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Biography

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