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A technology oriented productivity measurement model[1]

Wen-Chih Chiou[a,b,*], Hsiu-Wei Kuo[c], Iuan-Yuan Lu[b]

[a] *Department of Business Administration, National Chin-Yi Institute of Technology and Commerce, Kaohsiung, Taiwan, ROC*
[b] *Department of Business Administration, National Sun Yat-Sen University, Kaohsiung, Taiwan, ROC*
[c] *Department of Industrial Engineering, Feng-Chia University, Taichung, Taiwan, ROC*

Abstract

In this era of technological explosion, managers are faced with the challenge of how to maintain technological leadership and provide the best possible technology for the customer. This paper presents a practical approach to measuring the productivity of technology in product development. The approach takes advantage of quality function deployment and total productivity of Edosomwan (Integrating Productivity and Quality Management, Marcel Dekker, New York, 1987) to balance the market-pull and technology-push. The efficiency and effectiveness of technology development are measured. This information may support managers for the decision in the subsequent technology investments and divisional resource allocations. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Moving into the 21st century, technology strategy is predicted to be more important than before. To achieve better competitiveness, many researchers, for example [1–4], have pointed out the need for integrating technology strategy into business strategy. In addition, Cooper [5] describes the needs for balancing the technology-push and the market-pull in developing new product and new technology. It is significant that the customer-oriented management, which focuses on "quality competitiveness", becomes increasingly considerable in today's global markets.

As a result, two conclusions are addressed: (1) To verify and to select the key technology are the preemptive operations for formulating the technology strategies. (2) Measure the efficiency of new technology development is a momentous and necessary activity in the technology management.

Sumanth [6] states that the quality and productivity are commonly used as indicators for business performance. However, the development of technology covers usually many financial years and thus the traditional models fail to estimate its productivity. It also lacks models to estimate simultaneously

* Correspondence address: W.-C. Chiou, Department of Business Administration, National Sun Yat-Sen University, P.O. Box 59-197, Kaoshung, Taiwan, ROC. Tel.: 886 4 3912643; fax: 886 4 3915817; e-mail: chiouwc@chinyi.ncit.edu.tw.

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effectiveness as well as efficiency for new technology development. For this reason, this research attempts to develop a technology-oriented productivity measurement model which not only considers technology-push and market-pull in evaluating the key technology, but also measures the productivity for each key technology in its development periods.

2. Related research

According to Granstrand and Sjolanders [7], the key technologies are defined as technologies that directly influence the products' performances and/or quality. Key technologies can also attract customers to pay a premium price for those products or to differentiate the products from several competitors. Quality function deployment (QFD) can implement this definition properly [8]. In addition, both Lyman [9] and Wasserman [10] present a normalized transform method to compute the relationship values for the relationship matrix of QFD. The proposed approach integrates these methods to select key technologies and gives a proper relative important value to each key technology.

Edosomwan [11] presents a technology-oriented total productivity measurement model (TOTPM) to study the impacts of new technology on productivity growth. It is a complex model. Four indexes (i.e., i for technology type, j for technology life cycle phase, k for technology development-manufacturing-service site, t for study period) are used to estimate total productivity of technology for type i, in phase j, in site k, and in period t.

Although TOTPM can measure productivity, it is computationally burdensome in realistic situations. The impacts of technology may be on many products and the development works of technology may be in many divisions. Hence, we attempt to reserve the study period index and to simplify TOTPM by considering those key technology types associated with their related divisions.

Mandakovic and Souder [12] develop a model to measure R&D productivity. They also present a method to compute the overall outputs of R&D. Kuo [13] presents a framework to calculate resource for technology development. Those methods are applied to the proposed approach for collecting the data of input and output.

3. Proposed model

The proposed approach is presented in this section. Since it only measures the productivity of technology development, the approach is called technology oriented productivity measurement model (TOPMM).

3.1. Notations

The notations of TOPMM are described as follows:

c	= customer requirement ($c = 1, 2, 3, \ldots, n$).
d	= technology requirement ($d = 1, 2, 3, \ldots, m$).
D_j	= relative importance of important related division, j.
e	= technology requirement ($e = 1, 2, 3, \ldots, m$).
H_i	= degree of importance of key technology, i.
i	= key technology ($i = 1, 2, 3, \ldots, m$).
j	= key technology development important related division ($j = 1, 2, 3, \ldots, p$).
k	= key technology development related division ($k = 1, 2, 3, \ldots, p$).
$\gamma_{d,e}$	= correlation between technology requirement d and e.
$R^{T}_{c,d}$	= traditional quantified relationship between customer requirement, c, and technology requirement, d.
$R^{T}_{i,k}$	= traditional quantified relationship between key technology, i, and related division, k.
$R_{c,d}$	= normalized quantified relationship between customer requirement, c, and technology requirement, d.
$R_{i,k}$	= normalized quantified relationship between key technology, i, and related division, k.
RI_i	= relative importance of key technology, i.
t	= study period ($t = 1, 2, 3, \ldots, q$).
TIT_{ijt}	= total input utilized to produced key technology i, in important related division j, in period t.

TOT_{ijt} = total output of key technology i, produced in important related division j, in period t.
TPT_{ijt} = productivity of key technology i, in important related division j, in period t.
U_c = degree of importance of customer requirement, c.
W_d = absolute, important rating for technology requirement, d.
W_i = absolute, important rating for key technology, i.
W_j = absolute, important rating for important related division, j.
W_k = absolute, important rating for related division, k.

3.2. Implementation methodology

In this section, the implementation methodology for TOPMM is proposed. It can be divided into four portions. First, the customer's need of products is evaluated to verify the key technologies of the enterprise. Second, the relative important value of key technologies to each related division is calculated. Third, the data for inputs and outputs are collected. Fourth, the productivity is calculated.

A stepwise description of this methodology is given in the following. Furthermore, a teamwork-approach among divisions, managers, engineers, and experts of technology is strongly recommended to facilitate better results.

Step 1: Apply QFD to construct a quality house, and then use a normalized transform method to verify key technologies.

Step 2: Construct a relationship matrix between key technologies and related divisions and then use the normalized transform method to calculate the absolute important values of each related division. Considering these values and a given threshold value, managers can classify these related divisions into the important related division set and the weak important related division set.

Step 3: Breakdown works of technology development to each important related division. Perform input and output analysis associated with key technology to each important related division period by period. Identify all resources required to produce output.

Step 4: Collect the data of input and output for technology development periodically and then calculate TPT_{ijt}.

3.2.1. Verifying key technologies

The technologies are verified to match customers' satisfaction through the quality house of QFD. The normalized transform method of Wasserman [7] is applied to calculating each technologies' absolute important value. The team of decision making has to decide a threshold value (TV) based on the technology strategy of enterprise. The key technologies are selected whenever their absolute important values are greater than TV. By this way, market-pull (customers' demands), technology-push (technology demands) and business technology strategies are considered together in the selection of key technologies. It seems realistic.

The normalized transform method and decision rule are given in the following:

$$R_{c,d} = \sum_{e=1}^{m} (R^{T}_{c,e}\gamma_{e,d}) \Big/ \sum_{d=1}^{m}\sum_{e=1}^{m} (R^{T}_{c,d}\gamma_{d,e}), \tag{1}$$

$$W_d = \sum_{c=1}^{n} (U_c R_{c,d}). \tag{2}$$

For each d, if its $W_d \geqslant \text{TV}$, it can be verified as a key technology, i. The absolute, important rating for the key technology i can be expressed as W_i.

Considering the above results, the relative importance of each key technology, RI_i, can be re-calculated by the following equation:

$$RI_i = W_i \Big/ \sum_{i=1}^{m} W_i. \tag{3}$$

So, the degree of importance of each key technology, H_i, is equal to $RI_i * 100$. These values will be used in the next step.

3.2.2. Classifying related divisions

After the key technologies are decided, the relationship matrix of key technology and their related divisions are constructed to calculate each related divisions absolute important value. The matrix is augmented from the idea of QFD. For simplicity, we assume the correlation between each related division is equal to zero. Then, the normalized transform method of Lyman [9] is applied to calculating each related division's absolute important value. Comparing the absolute important values to a given threshold value (DTV), the related division's are then sorted into two sets: the important related division set (Ω) and the weak-important related division set (Φ).

The DTV is decided by the team of experts based on organization structure and strategy. Generally speaking, managers should pay more attention and perform a more detailed analysis to those important related divisions:

The normalized transform method and decision rule are given in the following:

$$R_{i,k} = R^{\mathrm{T}}_{i,k} \Big/ \sum_{k=1}^{p} R^{\mathrm{T}}_{i,k}, \tag{4}$$

$$W_k = \sum_{i=1}^{m} (H_i R_{i,k}). \tag{5}$$

For each k, if its $W_k \geqslant \mathrm{DTV}$, it can be classified as important related division, j. The absolute, important rating for important related division j can be expressed as W_j.

Considering the above results, the relative importance of each important related division, D_j, can be re-calculated by the following equation. In the next step, these values are used to allocate the expected market value of the key technology into its important related divisions.

$$D_j = W_j \Big/ \sum_{j=1}^{p} W_j. \tag{6}$$

3.2.3. Perform input and output analysis

The development works of each key technology is viewed as a project. We apply work breakdown structure method (WBS) [13] to build the working packages for projects. For each working package, managers have to plan the input resources and the expected output performance for each important related division during each period of the whole developing life cycle. Tables 1 and 2 present some example of measurable factors for TOPMM.

Table 1
Measurable inputs of TOPMM

1. Development expenses	6. Computers expenses
2. Labor expenses	7. Robotics expenses
3. Material expenses	8. Other forms of technology expenses
4. Capital expenses	9. Re-training expenses
5. Energy expenses	10. Other administrative expenses

Table 2
Measurable outputs of TOPMM

Divisions	Output components
R&D	New ideas, partially completed or finished model and prototype, publication and citation counts, number of patents and innovations, number of experiment reports.
Engineer	Number of technological patents and innovations, technical performance parameters, partially completed or finished model and prototype, partially completed or finished charts and graphics.
Manufacturing	Partial units, finished units, other output associated with units produced.
Marketing	Number of market survey reports, sales revenues.
Finance	Number of finance analysis or evaluation reports.
HRM	Number of training courses, employees, and times.

As you can see, the unit of measurable factor in Table 2 is quantity. The reason is that counting the number of periodic outputs is easier for managers. To calculate the periodic productivity, each periodic output performance has to be transformed to the equivalent market value. It is computationally burdensome in the implementation. To estimate periodic output values, two assumptions are proposed.

Assumption 1. In an ordinary way, the more important the division is, the more input resources the division requires.

Assumption 2. Following Assumption 1, the division gets more input resources, the more output values she needs to produce.

From Assumption 1, managers can base on the degree of importance of each important related division (D_j) to estimate input resource required for each important related division in each project's working package. From Assumption 2, the expected output value of each important related division should depend on the degree of importance of each important related division (D_j). Meanwhile, the "output achievement rate" [12] is used to adjust the expected periodic outputs derived by previous assumptions. The achievement rate is defined as a ratio between effective (real) outputs and the planned outputs. The values of outputs are then estimated as the products of expected market values and the achievement rate.

The detailed stepwise algorithm is given in the following.

Step 1. Apply the WBS method to build the working packages for each project. In each working package, managers refer to the degree of importance of each important related division (D_j) to estimate input resource required for each important related division in each period.

Step 2. In the beginning of each period, managers have to estimate each important related division's expected output performance during this period. They can set up these expected numbers based on Table 2.

Step 3. At the end of each period, managers collect each important related division's actual input data based on the items in Table 1.

Step 4. At the end of each period, managers collect each important related division's actual output performance. Then they can calculate the output achievement rate (A_{ijt}) by the following equation:

$$A_{ijt} = \mathrm{AOT}_{ijt}/\mathrm{POT}_{ijt} \tag{7}$$

where AOT_{ijt} is the actual output number of key technology i, in important related division j, in period t, and POT_{ijt} the planned output number of key technology i, in important related division j, in period t.

Step 5. At the end of each period, combine the actual input data in current period and the estimated input data in the subsequent periods, managers can calculate the input proportion of the current period. Meanwhile, managers need to estimate the total market value of each project (if each project can start up successfully). Then refer to the degree of importance of each important related division (D_j) to estimate the contributed market value of each important related division. Through the following equation, managers can get the desired periodic output value (EOV_{ijt}):

$$\mathrm{EOV}_{ijt} = \mathrm{EMV}_{it} D_j \mathrm{POP}_{ijt} A_{ijt} \tag{8}$$

where EMV_{it} is the estimated total market value of key technology i, in period t, and POP_{ijt} the input proportion of key technology i, in important related division j, in period t.

Step 6. After all the data of inputs and outputs are carefully collected, the periodic technology oriented productivity is measured by formula (9).

$$\mathrm{TPT}_{ijt} = \mathrm{TOT}_{ijt}/\mathrm{TIT}_{ijt} \tag{9}$$

By the above stepwise algorithm, managers can perform input/output analysis periodically and calculate the productivity of each key technology, in each important related division, and in each period. If managers want to calculate the productivity of each key technology, in all important related divisions, and in each period, they can apply the following formula:

$$\mathrm{TPT}_{it} = \sum_{j=1}^{p} (\mathrm{TOT}_{ijt}) \Big/ \sum_{j=1}^{p} (\mathrm{TIT}_{ijt}) \tag{10}$$

Managers can apply Eq. (11) to calculate the productivity of all key technologies, in all important related divisions, and in each period. To present each key technology's influence, the TOPMM value should be weighted by each key technology's degree of importance (H_i).

$$\mathrm{TPT}_t = \left[\sum_{i=1}^{m} H_i \left(\sum_{j=1}^{p} \mathrm{TOT}_{ijt}\right)\right] \Big/ \left[\sum_{i=1}^{m} H_i \left(\sum_{j=1}^{p} \mathrm{TIT}_{ijt}\right)\right]. \tag{11}$$

4. Example

A hypothetical case was designed to demonstrate the computation process of this technology oriented productivity measurement algorithm.

Step 1. The product planning matrix of a hypothetical infrared (IR) sensor alarm is illustrated in Fig. 1. Based upon results from a market survey, the important customer requirements – long distance of sensor, wide range of sensor, and short response time – are listed on the left-hand side of the matrix. For example, for each customer requirement, such as wide range of sensor, the design team must respond to this need by identifying the important technologies required, such as sensor material and outline design. If the requirements are fulfilled, this need will be fulfilled.

Through the traditional quantify method, we use a 1–3–9 scale to denote weak, strong, and very strong relationships between customer and technology requirement pairs. A 0.1–0.3–0.9 scale is also used to denote weak, strong, and very strong correlation between each technology requirement pair. Through Eqs. (1) and (2), the absolute important rating for technology requirements – sensor material, field effect transistor, high resistivity resistor, circuit design, and outline design are 25.7, 16.95, 17.8, 7.05, and 32.5, respectively. If the decision team assign the TV as 20, then it is verified that sensor material and outline design are key technologies based on the given decision rule.

According to the above information, managers can apply Eq. (3) to calculate the relative important rating of key technologies – sensor material and outline design, which are 0.44 and 0.56, respectively. So the degree of importance of these two key technologies, H_i, is equal to 44 and 56.

Step 2. We augment the QFD idea to construct a relationship matrix between key technologies and

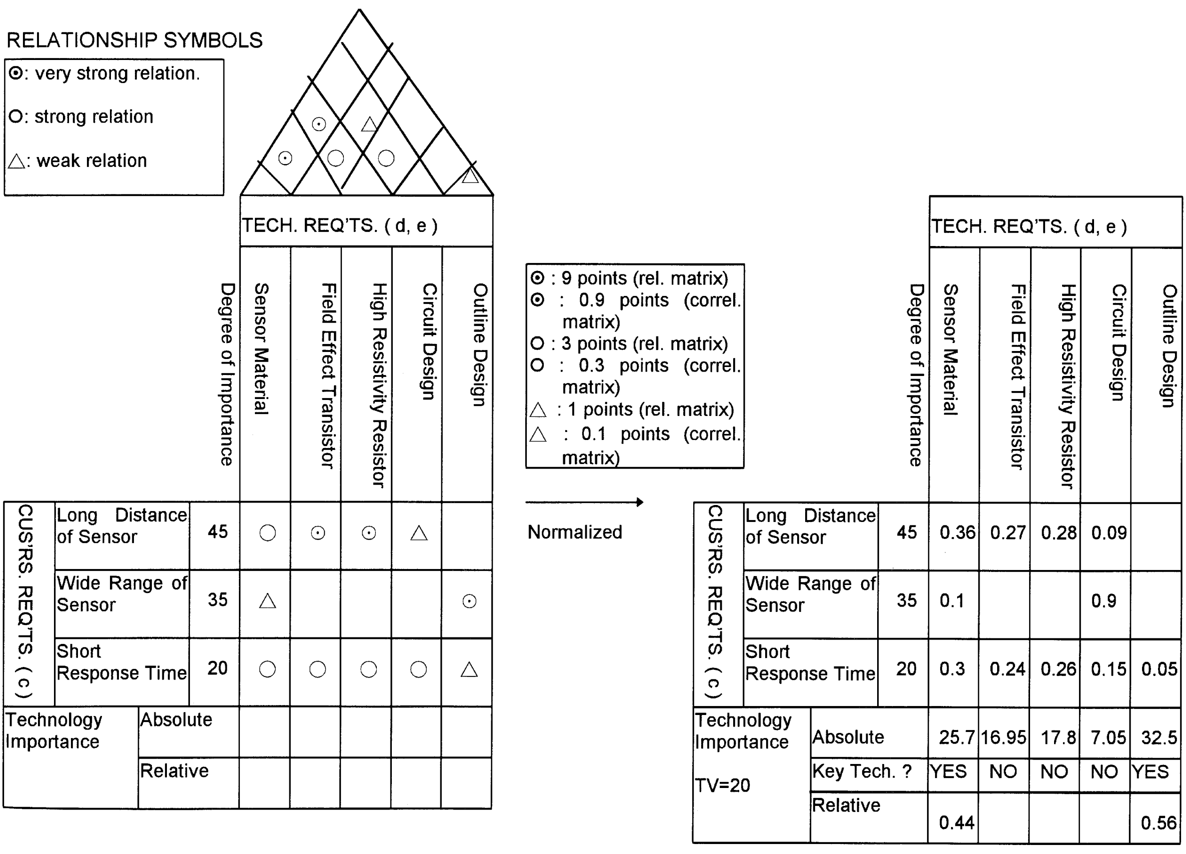

Fig. 1. QFD matrix for a hypothetical IR sensor alarm.

related divisions as shown in Fig. 2. Then the normalized transform method is used to calculate important values of each related division.

As shown in Fig. 2, through the traditional quantify method, a 1–3–9 scale is used to denote weak, strong, and very strong relationships between key technology and related division pairs. For simplicity, we assume the correlation between each related division pairs are all equal to zero. Through Eqs. (4) and (5), the absolute important rating for related divisions – R&D, engineering, manufacturing, marketing, finance, and human resource divisions are 24.6, 38.04, 12.83, 12.83, 5.83, and 5.83, respectively. If the decision team assign the threshold value (DTV) of 10, then the R&D, engineering, manufacturing, marketing divisions can be classified as important related divisions based on the given decision rule.

According to the above information, managers can apply Eq. (6) to calculate the relative important ratings of these four important related divisions – which are 0.27, 0.43, 0.15 and 0.15, respectively.

Step 3. For instance, the development schedules for both sensor materials (key technology 1, project 1) and outline design (key technology 2, project 2) are two periods of time, meanwhile assuming that both projects begin at the same time.

First, managers apply the WBS method to building the working packages for these two projects. Assume the total market value for key technology 1 and key technology 2 is expected to be $1000 and $1050. It has four important related divisions. Managers can consider the relative importance of each important related division to estimate the resource consumption for each key technology

⊙ : very strong relation
○ : strong relation
△ : weak relation

			Related Divisions (k)					
		Degree of Importance	R & D Division	Engineering Division	Manufacturing division	Marketing Division	Finance Division	Human Resource Div.
Key Technology. (i)	Sensor Material	44	⊙	○	△	△	△	△
	Outline Design	56		⊙	○	○	△	△
Related Division Importance	Absolute							
	Relative							

⊙ : 9 points (rel. matrix)
○ : 3 points (rel. matrix)
△ : 1 points (rel. matrix)

→ Normalized

			Related Divisions (k)					
		Degree of Importance	R & D Division	Engineering Division	Manufacturing division	Marketing Division	Finance Division	Human Resource Div.
Key Technology. (i)	Sensor Material	44	0.56	0.19	.0625	.0625	.0625	.0625
	Outline Design	56		0.53	0.18	0.18	.055	.055
Related Division Importance DTV=10	Absolute		24.64	38.04	12.83	12.83	5.83	5.83
	Important or Weak Imp't. ?		Imp't.	Imp't.	Imp't.	Imp't.	W.I.	W.I.
	Relative		0.27	0.43	0.15	0.15		

Fig. 2. Relationship matrix for key technologies and related divisions.

development. The period 1 working package of these two projects is presented in Tables 3 and 4.

According to Eq. (7), managers calculate the output achievement rate of each key technology, in each important related division, in period 1. Assume the output achievement rate for key technology 1, in each important related division, in period 1 is 0.95, 0.9, 0 (manufacturing division has not input/output data in period 1), 0.9. The output achievement rate for key technology 2, in each important related division, in period 1 is 1, 0.9, 0 (manufacturing division has not input/output data in period 1), 0.94.

So, based on Eq. (8), the expected output values of key technology 1, for each important related division, at period 1 are estimated as \$256.5 (= \$1000 × 0.27 × 1 × 0.95), \$112.23 (= \$1000 × 0.43 × 0.29 × 0.9), \$0 (= \$1000 × 0.15 × 0 × 0), and \$67.5 (\$1000 × 0.15 × 0.5 × 0.9), respectively. According to this pattern, the expected output values of key technology 2, for each important related division, at period 1 are estimated as \$212.63 (= \$1050 × 0.27 × 0.75 × 1), \$117.84 (= \$1050 × 0.43 × 0.29 × 0.9), \$0 (= \$1050 × 0.15 × 0 × 0), and \$74.03 (= \$1050 × 0.15 × 0.5 × 0.94).

Finally, all the data of periodic inputs and outputs are collected carefully. The productivity of each key technology, in each important related division, in period 1 is calculated by using Eq. (9). The result was shown in Tables 5 and 6. This information can provide managers to adjust the allocation of the next period's input resources to each important related division.

If managers want to understand the productivity of each key technology, in all important related division, in period 1, then they can apply Eq. (10) to achieve this work. The result is presented in Table 7. This information can provide managers with the evaluation of each key technology's develop performance.

If managers want to understand the productivity of all key technology, in all important related divisions, in period 1, then they can apply Eq. (11) to achieve this work. The result is presented in Table 8. This information can provide managers with the evaluation of the whole business's technology

Table 3
Key technology 1, the real input for period 1 and the planned input for period 2

	R&D ($j = 1$)	Eng. ($j = 2$)	Mfg. ($j = 3$)	Mkt. ($j = 3$)
$t = 1$	30 (100%)	10 (29%)	—	5 (50%)
$t = 2$	—	25 (71%)	20 (100%)	5 (50%)
Total	30	35	20	10
D_j	27%	43%	15%	15%

D_j: Relative important values for division j
(%): POP_{1j1}, the input proportion of key technology 1, in important related division j, in period 1.

Table 4
Key technology 2, the real input for period 1 and the planned input for period 2

	R&D ($j = 1$)	Eng. ($j = 2$)	Mfg. ($j = 3$)	Mkt. ($j = 3$)
$t = 1$	15 (75%)	10 (29%)	—	5 (50%)
$t = 2$	5 (25%)	25 (71%)	15 (100%)	5 (50%)
Total	20	35	15	10
D_j	27%	43%	15%	15%

D_j : Relative important values for division j.
(%): POP_{2j1}, the input proportion of key technology 2, in important related division j, in period 1.

Table 5
Productivity of key technology 1, in each important related division, in period 1

	R&D ($j = 1$)	Eng. ($j = 2$)	Mfg. ($j = 3$)	Mkt. ($j = 4$)
TPT_{1j1}	8.55 (= 256.5/30)	11.22 (= 112.23/10)	0	13.5 (= 67.5/5)

Table 6
Productivity of key technology 2, in each important related division, in period 1

	R&D ($j = 1$)	Eng. ($j = 2$)	Mfg. ($j = 3$)	Mkt. ($j = 4$)
TPT_{2j1}	14.2 (= 212.63/15)	11.8 (= 117.84/10)	0	14.8 (= 74.03/5)

Table 7
Productivity of key technology 1 and of key technology 2, in all important related division, in period 1

	Key technology 1 ($i = 1$)	Key technology 2 ($i = 2$)
TPT_{i1}	9.7 [= (256.5 + 112.23 + 67.5)/(30 + 10 + 5)]	13.5 [= (212.63 + 117.84 + 74.03)/(15 + 10 + 5)]

Table 8
Productivity of all key technology, in all important related division, in period 1

	Period 1 ($t = 1$)
TPT_1	11.43 { = [(436.23 × 0.44) + (404.5 × 0.56)]/[(45 × 0.44) + (30 × 0.56)]}

develop performance. In the same way, the TOPMM value for period 2 can be computed.

5. Conclusion

This paper presents a practical approach to measure the productivity for the key technology of an enterprise. The approach verifies key technology, estimates the relative important values to important related divisions, and calculates productivity for key technology and for important related divisions. Since the approach evaluates technology-pull and market-push, the measured productivity is more useful for management.

The TOPMM model is a powerful model with strong potential for application to various product groups, tasks, and projects in both manufacturing and service organizations. For each potential implementation case, minor modification may have to be made in data collection items and instruments.

Although this work has simplified Edosomwan's [11] original computation methodology, the calculation for TOPMM is still complex. It seems practical, if TOPMM is implemented with the information system of the enterprise.

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