A NEW METHOD FOR MONITORING INDUSTRIAL PRODUCT-SERVICE SYSTEMS BASED ON BSC AND AHP

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Abstract: Driven by the increased competition pressure in the last few years, a number of manufactures are shifting their focus from products towards Industrial Product-Service Systems (IPS²). However, the shift to IPS² is also accompanied by risks. The monitoring of IPS² could support executives in identifying the IPS² risks in time and could serve as the basis for optimizing future IPS². In this paper a new method for the hierarchical monitoring of IPS² is developed based on Balanced Scorecard (BSC) and Analytic Hierarchical Process (AHP). The performances and the imbalance degrees of IPS² on different levels are calculated to show IPS² comprehensively. BSC is applied to define IPS²-specific perspectives and indicators. AHP is used to construct a hierarchical monitoring structure and to generate weights for different IPS²-specific perspectives and indicators. Finally a case study is introduced to validate this method.

1 INTRODUCTION

An Industrial Product-Service System (IPS²) is defined as "an integrated offering of product and service that delivers values in industrial application" (Meier et al., 2010). It can also be considered as an innovation that extends the traditional functionality of a physical industrial product by incorporating additional services (Baines et al., 2007). The shift to IPS² can enhance competition and generate more customer benefits, but complex combination among different products and services in IPS² increases the risks (Cook et al., 2006; Sundin et al., 2009). A quick and precise monitoring of IPS² could support executives in identifying the IPS² risks in time and could serve as a basis for optimizing future IPS². At present, however, executives of IPS² suppliers can only gain IPS²-related information from reports submitted by their employees. It largely impairs executives' work efficiency in monitoring IPS². Hence, a new method for monitoring IPS² is urgently needed.

This paper proposes a new hierarchical monitoring method with three levels (i.e. the overall IPS² level, the perspective level and the indicator level) based on Balanced Scorecard (BSC) and Analytic Hierarchical Process (AHP) for executives to monitor IPS² quickly and precisely. BSC has been applied to define IPS²-specific perspectives and indicators. AHP has been used to construct the hierarchical monitoring structure based on these IPS²-specific perspectives and indicators and to generate weights for them. In order to process the indicators with different measurement units, percentages are used to standardize the measurement of different indicators. Furthermore, executives need to know about the imbalances among the various aspects, so that they can determine whether IPS² is running in balance or not. Thus, the performances and the imbalance degrees of IPS² on different levels are both calculated to show the status of IPS² comprehensively. To verify this new method, the paper concludes with a case study about the monitoring of micro-machining PSS.

2 RELATED WORKS

2.1 The Balanced Scorecard (BSC)

The Balanced Scorecard was introduced by Kaplan and Norton (1992) as a management system to align an organization's performance measures with its strategic plan and goals. As exclusive reliance on financial measures in a management system is insufficient, the BSC highlights a balance between

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financial indicators and non-financial indicators (Craig and Moores, 2010; Yang, 2009). The BSC suggests that an organization should be evaluated from four different perspectives: financial perspective, customer perspective, perspective of internal processes and perspective of learning and growth. Each perspective considers several related performance measuring indicators.

Though originally developed as a performance measurement tool, the BSC has evolved into an organizing framework, an operating system, and even a strategic management system (Kaplan and Norton, 1996). Of course, the choice and definition of the perspectives and indicators depend on the characteristics of the individual BSC implementation. BSC can be adapted as a tool for executives to monitor IPS², but the main weakness that all indicators have the same weight hides the different importance of the considered indicators.

2.2 The Analytic Hierarchical Process (AHP)

The AHP method was developed by Saaty (1980) as a tool for modeling the complex decision problems. It allows both qualitative and quantitative approaches to solve complex decision problems (Wong and Li, 2008). In the qualitative aspect, the problem is modeled to a hierarchy consisting of an overall goal, a group of criteria and sub-criteria, and a group of alternatives. In the quantitative aspect, numerical weights for criteria are generated by making pairwise comparisons among all criteria at each level to distinguish in general the more important criteria from the less important ones.

To improve validity recognizing that participants may be uncertain or make poor judgments in some of the comparisons, redundant comparisons are involved in AHP. This redundancy can lead to numerical inconsistencies. Saaty (1994) suggested the error in these measurements is tolerable only when it is of a lower order of magnitude (0.1) than the actual measurement itself.

In order to distinguish the more important indicators in the monitoring of IPS² from the less important ones, the AHP method is mainly used to generate weights for all indicators and perspectives (Wang, 2009). The above-mentioned process of weight generation and verification can ensure that all weights are assigned meaningfully and objectively.

3 THE MONITORING METHOD FOR IPS²

3.1 The IPS²-specific BSC

For the monitoring and measuring the performance of IPS², executives require different information in different perspectives. With reference to the structure of BSC, as recommended by Kaplan and Norton, four specific perspectives have been considered for the IPS²-specific BSC: the customer perspective, the perspective of IPS² lifecycle, the perspective of IPS² resources and the financial perspective (figure 1). The overall IPS² goal takes a central position.

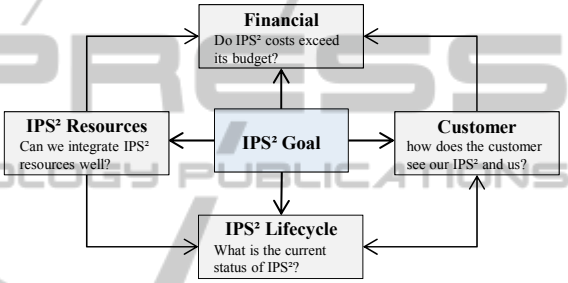

Figure 1: The IPS²-specific BSC perspectives.

In general, the fulfillment of customer needs and customer satisfaction are the main goals of an IPS² offering. The quality of the IPS² affects customer satisfaction directly. The acquisition and integration of different IPS² resources are prerequisites for each successful IPS². They are also the foundation of the innovation and creativity for IPS². Moreover, the high efficiency of IPS² resources can reduce cost and improve the financial status. Satisfied and loyal customers can also lead to increased revenues, i.e. improvement of the financial status. The balance of these four perspectives can ensure a successful IPS².

In order to measure and monitor the IPS² performance, several indicators have been defined and assigned to considered perspective. In order to explain the monitoring process clearly, only three to four indicators have been shown in figure 2. Generally, indicators can be divided into two categories: quantitative indicators and qualitative indicators (CIDA, 1996).

- Quantitative indicators can be defined as measure of quantity, such as revenue of IPS².
- Qualitative indicators can be defined as people's judgments and perceptions about a subject, such as customer satisfaction.

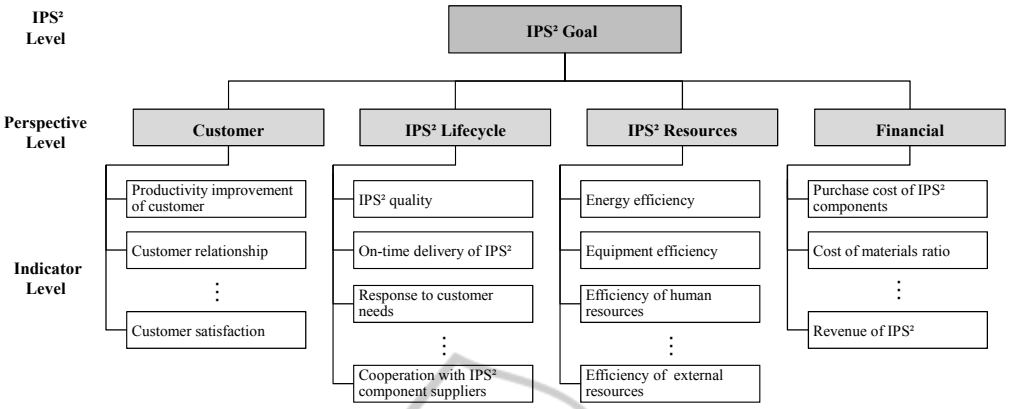

Figure 2: The three-level structure of the monitoring method (adapted from Yuan and Chiu, 2009).

3.2 Three-level Structure of the Monitoring Method

According to the structure of the IPS²-specific BSC, a hierarchical structure incorporating three-levels has been constructed for this monitoring method, as shown in figure 2. The first level is the overall IPS² goal. The second level shows four perspectives in agreement with the IPS²-specific BSC. The third level defines performance measuring indicators.

Usually the performance of an indicator is its actual value. Since different indicators have different measurement units, it is impossible to compare and to integrate indicators with different units. Thus, percentage is used to unify the measurement of all indicators. In this method the performance of an indicator can be calculated as follows:

If $a>t$ is the most expected result

$$p = (1 - \frac{t-a}{t}) \times 100\% \quad (1)$$

If $a<t$ is the most expected result

$$p = (1 + \frac{t-a}{t}) \times 100\% \quad (2)$$

Where p: performance, t: target, a: actual value

As an example, the performance of "On-time delivery of IPS²" indicator can be calculated using (2) and based on the target finish time and the actual finish time. All quantitative indicators can be measured using similar calculation. However, for qualitative indicators these two equations cannot be used, but their principles must be kept. The performance of qualitative indicators should be manually measured according to their measurement standards, and then converted to percentages.

The performance of indicators is the basis for the further calculation. The performance of each perspective is the weighted average of all indictors under it. The overall performance is the weighted average of its four perspectives.

Within the BSC method all indicators and perspectives have the same weight. In fact different indicators or perspectives have different weights. The assignment of weights provides executives with more precise information about the performance of IPS². The AHP method is used to generate the weights. Since indicators are organized by the perspectives, the indicators in different perspectives are not associative. The weights of perspectives and the weights of indicators under each perspective should be generated separately.

In order to show the imbalance among different indicators or perspectives, the imbalance degree are calculated using the method of standard variance that is usually used as a measure of how far a set of numbers are spread out from each other.

The hierarchical structure gives executives a top-down view to monitor IPS². Based on the performances of IPS² on these three levels, executives can determine whether the IPS² has been well implemented or not. At the same time the imbalance degree show executives whether IPS² has been implemented in a balanced way or not.

3.3 Methodology

By combining the BSC and the AHP method and adapting them to IPS², a five-step calculation method has been developed to generate the weights of different indicators and perspectives, and to calculate the performances and imbalance degrees of IPS² on different levels.

The performances and imbalance degrees of the overall IPS², the customer perspective, the IPS² lifecycle perspective, the IPS² resources perspective and the financial perspective must be calculated

separately. Since their calculation process are the same, the customer perspective serves as an example to explain this calculation method.

Step 1: Construct the Comparison Matrix

The comparison matrix is constructed based on the pairwise comparisons of each two indicators. It is the prerequisite for the calculation of weights. In order to determine the quantitative matrix, a standardized comparison scale of nine levels is used (table1).

If the number of customer indicators is n, the pairwise comparison matrix is an $n \times n$ matrix C. Where c_{ij} represents relative importance between indicator I_i and I_j. This matrix C satisfies:

$$c_{ij} > 0, c_{ij} = 1/c_{ji}, i, j = 1, 2, \cdots, n.$$

Table 1: The comparison scale for the comparison matrix (Saaty, 1980).

Element	Numerical scale	Meaning
c_{ij}	1	I_i has equal importance as I_j
	3	I_i has moderately more importance as I_j
	5	I_i has strongly more importance as I_j
	7	I_i has very strongly more importance as I_j
	9	I_i has extremely more importance as I_j
	2, 4, 6 and 8	Intermediate values between two successive qualitative judgments

Step 2: Calculate the Weight Vector

The comparison matrix of the customer indicators is the matrix C. W_c is the weight vector of customer indicators. The weight of indicator I_i can be calculated as (3):

$$w_i = \frac{v_i}{\sum_{i=1}^{n} v_i}$$
$$\text{where } v_i = \sum_{j=0}^{n} c_{ij} \text{ and } \sum_{i=1}^{n} w_i = 1 \quad (3)$$

Step 3: Examine the Consistency Ratio

The consistency property of the matrix is then verified to ensure the consistency of judgments in the pairwise comparison. The Consistency Ratio (CR) are defined as (4):

$$CR = \frac{CI}{RI} \quad (4)$$

$$\text{where } CI = \frac{\lambda_{max} - n}{n-1}$$

CI (Consistency Index) is the average consistency. λ_{max} is the maximum eigen value of the comparison matrix, and n is the size of matrix. RI is the average random index taken as in Table 2.

If $CR < 0.1$, the comparison matrix is considered to be consistent. In contrast, the matrix results are inconsistent and it needs to be modified for the further analysis.

Table 2: Random Index values for matrix (Saaty, 2008).

Size of matrix (n)	1	2	3	4	5
RI	-	-	0.58	0.9	1.12
Size of matrix (n)	6	7	8	9	10
RI	1.24	1.32	1.41	1.45	1.49

Step 4: Calculate the Performance

If the comparison matrix is consistent, it can be used for the calculation of the performance of the customer perspective. The performance of all customer indicators should be calculated beforehand. If $P_{ic} = \{p_1, p_2, \ldots, p_n\}$ is the performance vector of customer indicators, the performance of the customer perspective can be calculated using the following equation (5):

$$P_c = E(P_{ic}) = P_{ic} \cdot W_c^{\intercal} \quad (5)$$

Step 5: Calculate the Imbalance Degree

In essence, the imbalance degree of the customer perspective is the standard variance of all customer indicators. Their weighted variance is calculated using (6). Subsequently their standard variance can be calculated using (7):

$$\sigma_c^2 = \frac{\sum_{i=1}^{n} w_i (p_i - E(P_{ic}))^2}{\sum_{i=1}^{n} w_i} \quad (6)$$

Where $\sum_{i=1}^{n} w_i = 1$, then:

$$\sigma_c{}^2 = \sum_{i=1}^{n} w_i (p_i - P_c)^2$$

$$\sigma_c = \sqrt{\sum_{i=1}^{n} w_i (p_i - P_c)^2} \quad (7)$$

By using the same process, the performance of the IPS² lifecycle perspective, the perspective of IPS² resources and the financial perspective can be calculated as P_l, P_r and P_f respectively. Their imbalances can also be calculated as σ_l, σ_r and σ_f.

The overall performance and imbalance degree of IPS² can be calculated using equations (8) and (9):

$$P_{IPSS} = P_p \cdot W_p^{\intercal} \quad (8)$$

where P_p is the performance vector of four

perspectives:

$P_p = \{p_1, p_2, p_3, p_4\} = \{P_c, P_l, P_r, P_f\}$

W_p is the weight vector of perspectives

$$\sigma_f = \sqrt{\sum_{i=1}^{4} w_i (p_i - P_{IPSS})^2} \quad (9)$$

4 APPLICATION OF THE PROPOSED METHOD

In order to verify this method, it has been prototypically applied to monitor the micro-manufacturing PSS (Product-Service System) that is provided by MicroMan solutions Co. This IPS² offers customers an integrated solution including micro-machining technology and related services, such as condition monitoring, financing, process optimization, maintenance, training, and so on.

This monitoring method has been applied based on the structure shown in figure 2. Tables 3-7 show the comparison matrixes of customer indicators, IPS² lifecycle indicators, IPS² resource indicators, financial indicators, and perspectives respectively, which are created by several experts in the field of IPS². Their weight vectors are calculated using equation (3) and are listed as follows:

- $W_c = \{0.64, 0.12, 0.24\}$
- $W_l = \{0.43, 0.16, 0.33, 0.09\}$
- $W_r = \{0.26, 0.16, 0.49, 0.08\}$
- $W_f = \{0.55, 0.23, 0.22\}$
- $W_p = \{0.36, 0.12, 0.21, 0.31\}$

Table 3: The comparison matrix of customer indicators.

Customer	I_1	I_2	I_3
I_1	1	8	3
I_2	1/8	1	1/5
I_3	1/3	5	1

I_1: Productivity improvement of customer

I_2: Customer relationship, I_3: Customer satisfaction

Table 4: The comparison matrix of IPS² lifecycle indicators.

IPS² Lifecycle	I_1	I_2	I_3	I_4
I_1	1	3	1	5
I_2	1/3	1	1/3	2
I_3	1	3	1	3
I_4	1/5	1/2	1/3	1

I_1: IPS² quality, I_2: On-time delivery of IPS²

I_3: Response to customer needs

I_4: Cooperation with IPS² component suppliers

Table 5: The comparison matrix of IPS² resource indicators.

IPS² Resource	I_1	I_2	I_3	I_4
I_1	1	2	1/3	3
I_2	1/2	1	1/4	2
I_3	3	4	1	5
I_4	1/3	1/2	1/5	1

I_1: Energy efficiency, I_2: Equipment efficiency

I_3: Efficiency of human resources, I_4: Efficiency of external resources

Table 6: The comparison matrix of financial indicators.

Financial	I_1	I_2	I_3
I_1	1	2	3
I_2	1/2	1	1
I_3	1/3	1	1

I_1: Purchase cost of IPS² components

I_2: Cost of materials ratio, I_3: Revenue of IPS²

Table 7: The comparison matrix of perspectives.

Perspective	P_1	P_2	P_3	P_4
P_1	1	2	3	1
P_2	1/2	1	1/2	1/2
P_3	1/3	2	1	1/2
P_4	1	2	2	1

P_1: Customer, P_2: IPS² lifecycle, P_3: IPS² resources, P_4: Financial

In order to examine the consistency ratio of their comparison matrix, their *CR* values are calculated as follows:

- $CR_c = 0.034$
- $CR_l = 0.018$
- $CR_r = 0.019$
- $CR_f = 0.016$
- $CR_p = 0.044$

None of the values exceed 0.1. Thus, these five matrixes are considered consistent, and the five calculated weight vectors can be used to calculate the performance and imbalance degree of IPS² on different levels.

For a micro-machining PSS, the performance of its all indicators have been calculated and listed in column 5 of table 8. Column 4 shows the weight of each indicator. The performance and imbalance degree of each perspective have been calculated using equations (5) and (7), and are listed in column 2. The overall performance and imbalance degree have been calculated using equations (8) and (9) based on the results of column 2. They are shown in column 1 of table 8.

In comparison to the above calculation, the monitoring process is a top-down process. From column 1, executives can derive the overall status of IPS². Critical values can be taken to identify those IPS² that have poor performance or are not in

Table 8: The calculation of the performances and imbalance degrees for a micro-machining PSS.

IPS²	Perspective	Indicator	Weight	Performance
$P_{IPSS} = 96.0\%$ σ_{IPSS} =0.0879	Customer ($w_c = 0.36$) P_c =107.0% $\sigma_c = 0.049$	Productivity improvement of customer	0.64	110%
		Customer relationship	0.12	95%
		Customer satisfaction	0.24	105%
	IPS² Lifecycle ($w_l = 0.12$) $P_l = 96.1\%$ σ_l =0.092	IPS² quality	0.43	100%
		On-time delivery of IPS²	0.16	80%
		Response to customer needs	0.33	100%
		Cooperation with IPS² component suppliers	0.09	85%
	IPS² Resources ($w_r = 0.21$) $P_r = 85.4\%$ σ_r =0.042	Energy efficiency	0.26	84%
		Equipment efficiency	0.16	95%
		Efficiency of human resources	0.49	84%
		Efficiency of external resources	0.08	90%
	Financial ($w_f = 0.31$) P_f =90.3% σ_f =0.013	Purchase cost of IPS² components	0.55	85%
		Cost of materials ratio	0.23	113%
		Revenue of IPS²	0.22	80%

balance. Usually P_{IPSS} should not fall below 95% and σ_{IPSS} should not exceed 0.1. Column 2 provides executives with more detailed information of IPS², i.e. its four perspectives. Using critical values, problematic perspectives can be found out easily. The performance of each indicator in column 5 shows a concrete measurement of IPS². Executives can find the concrete problem of a problematical IPS² from the indicators whose performance is insufficient. That way, executives can determine problematic IPS² quickly and fix the problems precisely by using the proposed hierarchical monitoring method.

5 CONCLUSIONS

This paper has introduced a new method for the hierarchical monitoring of IPS² based on BSC and AHP to meet the IPS² monitoring requirements of executives. The BSC method offers a framework to comprehensively and precisely define IPS²-specific perspectives and indicators. The assignment of weights to different indicators and perspectives gives executives an opportunity to monitor and to measure the performance of IPS² by highlight in indicators or perspectives with different weights, and the AHP method ensures the generation of meaningful and objective weights. Moreover, the use of percentages as the unified measurement unit eliminates the measurement differences among different indicators and simplifies the expression of IPS² performances. Next to performances, imbalance degrees of IPS² have been calculated on different levels to offer executives a fast view of whether IPS² is running in balance or not.

The AHP employs a suitable method (i.e. pairwise comparison matrix and consistency examination) to ensure the generation of objective weights. If, however, a comparison matrix is very big, it is highly complex and a lot of time is needed to adjust it to pass consistency examination. Thus, an easier method for weight generation should be added in future as an alternative to avoid having to deal with too large comparison matrixes.

Since the main information, which is required by executives in IPS² monitoring, originates from the IPS² lifecycle management (LM) platform (Abramovici et al., 2008; Abramovici et al., 2009), it seems to be very efficient to integrate this monitoring method in the IPS² LM platform. Thus, in future, this monitoring method will be programmed as a function module in the IPS² LM platform to validate and to improve it in the actual application by IPS² suppliers. As executives tend to pay more attention to their products after the economic crisis, the described monitoring method can be adjusted and used further in other areas to monitor different products or services.

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REFERENCES

Abramovici, M., Michele, J., and Neubach, M., 2008. Extension of the Product Lifecycle Management Approach for PSS – Requirements and Challenges, *In Seminar Proceeding of Product Service Systems*.

Abramovici, M., Neubach, M., Schulze, M., and Spura, C., 2009. Metadata Reference Model for IPS² Lifecycle Management, *In Proceedings of the 1st CIRP IPS2 Conference*.

Baines, T. S., Lightfoot, H. W., Evans, S., and Neely, A., 2007. State-of-the-Art in Product-Service Systems, *Proc. IMechE Part B: Journal of Engineering Manufacture,* Vol. 221 No. 10, pp. 1543–1552.

CIDA, 1996. *Guide to Gender-Sensitive Indicators*, CIDA. Quebec.

Cook, M., Bhamra, T., and Lemon, M., 2006. The Transfer and Application of Product Service-systems: from Academia to UK Manufacturing Firms, *Journal of Cleaner Production,* Vol. 14 No. 17, pp. 1455–1465.

Craig, J., and Moores, K., 2010. Strategically Aligning Family and Business Systems Using the Balanced Scorecard, *Journal of Family Business Strategy,* Vol.1 No. 2, pp. 78–87.

Kaplan, R. S., and Norton, D. P., 1996. Using the Balanced Scorecard as a Strategic Management System, *Harvard Business Review*, pp. 75–85.

Kaplan, R. S., and Norton, D. P., 1992. The Balanced Scorecard Measures that Drive Performance, *Harvard Business Review*, pp. 71–79.

Meier, H., Roy, R., and Seliger, G., 2010. Industrial Product-Service System - IPS², *CIRP Annals - Manufacturing Technology*, Vol.59, pp. 607–627.

Michalska, J., 2005. The Usage of the Balanced Scorecard for the Estimation of the Enterprise's Effectiveness, *Journal of Materials Processing Technology,* Vol. 162, pp. 751–758.

Saaty, T. L., 1980. *The Analytic Hierarchy Process: Planning Setting Priorities, Resource Allocation*, Mcgraw-Hil. New York.

Saaty, T. L., 1994. How to Make a Decision: The Analytic Hierarchy Process, *Interfaces,* Vol. 24 No. 6, pp. 19–43.

Saaty, T. L., 2008. Relative Measurement and Its Generalization in Decision Making. Why Pairwise Comparisons are Central in Mathematics for the Measurement of Intangible Factors. The Analytic Hierarchy/Network Process, *Rev. R. Acad. Cien. Serie A. Mat.,* Vol. 102 No. 2, pp. 251–318.

Sundin, E., Sandström, G. Ö., Lindahl, M., Sakao, T., Rönnbäck, A. Ö., and Larsson, T. C., 2009. Challenges for Industrial Product/Service Systems: Experience from a Learning Network of Large Companies, *In Proceedings of the 1st CIRP IPS2 Conference*.

Wang, Y., and Xia, Q., 2009. A Fuzzy AHP and BSC Approach for Evaluating Performance of a Software Company Based on Knowledge Management, *In Proceedings of 1st International Conference on Information Science and Engineering.*

Wong, J., and Li, H., 2008. Application of the Analytic Hierarchy Process (AHP) in Multi-Criteria Analysis of the Selection of Intelligent Building Systems, *Building and Environment,* Vol. 43 No. 1, pp. 108–125.

Yang, J. H., 2009. A Balanced Performance Measurement Scorecard Approach for Product Service Systems, *In Proceedings of International Conference on Business Intelligence and Financial Engineering*.

Yuan, F., and Chiu, C., 2009. A hierarchical Design of Case-Based Reasoning in the Balanced Scorecard Application, *Expert Systems with Applications,* Vol. 36 No. 1, pp. 333–342.