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A study of enterprise resource planning (ERP) system performance measurement using the quantitative balanced scorecard approach

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ABSTRACT

Enterprise resource planning (ERP) systems have been used in integrating information and accelerating its distribution across functions and departments with the aim to increase organizations' operational performance. Thus, it is worth measuring ERP system performance based on its impact to critical performance of an organization: this requires a systematic method that bridges ERP performance measurement and key organizational performance. The hierarchical balanced scorecard (HBSC) model with respect to multiple criteria decision-making is such a systematic approach to ERP performance measurement. An ERP evaluation framework that integrates the balanced scorecard dimensions, linguistic variables, and non-additive fuzzy integral provides an objective approach to measuring both the performance level of the ERP system and its contribution to the strategic objectives of high-tech firms. Taking Taiwan's high-tech firms as an example, this study demonstrates the effectiveness of this integrated approach to measure the performance of ERP systems at the post-implementation stage under evaluators' subjective, uncertainty, and vagueness judgments.

1. Introduction

The high-tech industry has played a central role in the economic development of Taiwan in recent decades. However, the characteristics of this industry include shorter product life cycles, increasing global competitive pressure, and a variety of customer demands. In response to these trends, numerous high-tech firms in Taiwan have accelerated the integration of production and manufacturing information through the use of enterprise resource planning (ERP) systems across the entire firm, in order to maintain a long-term competitive advantage. ERP is a tool to standardize and integrate business processes to accelerate access to common resources across the organization so that ERP systems help organizations facilitate information sharing and improve operational efficiency [8]. The successful deployment and use of ERP systems is critical to organizational performance and survival [42]. ERP is increasingly important in modern business because of its ability to integrate the flow of material, finance, and information to support organizational strategies [78,80]. Davenport [16] reported that many ERP vendors, such as SAP, Baan, Oracle, and People-Soft, provided commercial software packages to favor the seamless integration of all the information flowing across a company's different functions. Take SAP's R/3 package as an instance, it supports the integration of information flows across a company's functions, including financials, human resources, operations and logistics, sales and marketing. These commercial ERP packages promise an "off-the-shelf" solution to the problem of business integration for managers who have struggled, at great expense and with great frustration, to coordinate incompatible information systems and inconsistent operating practices [16]. For serving as the organization's platform to support such cross-functional integration, ERP architecture enables different business applications to share a common database.

Various studies have asserted that ERP systems can increase competitive advantage in the information technology (IT) era. Particularly in the e-business era, there has been a global trend to integrate business processes based on the company's strategic implementation. A review of the potential benefits from ERP implementation can be classified into tangible and intangible benefits [1,67]. Tangible benefits include reduction of inventory, reduction of personnel, increased productivity, improvements in orders management, quicker closing of financial cycles, increase of 'on-time' deliveries, improved customer service, reduction in IT and procurement costs, improvement of cash flow management,

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increase of revenue and profits, reduction in transportation and logistic costs, and reduction in the need for system maintenance. Intangible benefits refer to the increased visibility of corporate data, new or improved business processes, improved responsiveness to customers, improved communications, unanticipated reduction in costs, better integration between systems, standardization of computing platforms, increased flexibility, global sharing of information, improved business performance, and improved visibility into the SCM process [1]. Despite these significant benefits, one major problem is that ERP systems cannot measure the performance which the systems impact on the firms. As Davenport [16] pointed out, many companies failed to consider whether the system they were evaluating will match their overall business strategy. The balanced scorecard (BSC) approach, though, is designed to support a variety of organizational performance measurement structures. The original BSC, proposed by Kaplan and Norton [33], was a performance measurement system consisting of four dimensions: financial, customer, internal business processes, and innovation and learning. It became a popular performance assessment technique because it was not only easy to implement across different departments but also provided a well-defined framework through integrating the tangible and intangible perspectives and delivering the firm's objectives, and therefore giving the business a competitive advantage. Chand et al. [8] thus argued that the BSC approach may be an appropriate technique for evaluating the performance of ERP systems, if well-defined performance measurement and related indicators are used to keep the strategic targets on track.

In theory, it is difficult to quantify information systems (IS) due to the intangible nature of many of the benefits, such as improved customer satisfaction. By applying the fuzzy set theory, this research undertakes an empirical study of numerous high-tech firms with the aim of systematically measuring ERP system performance via decision-makers' evaluations, taking the intangibles and tangibles into account. Furthermore, the BSC proposed by Kaplan and Norton [33] argues that the interrelationships exist among financial, customer, internal business process, and learning and growth perspectives. Additionally, there are many situations where observations cannot be described accurately as, for instance, when they depend on environmental conditions or on individual responses [68]. Specially, the BSC framework employed in this study relies on evaluators' subjective judgments, the imprecise and vague nature embedded in human perception is inevitable. Therefore, fuzzy linguistic variable scale proposed by Hersh and Caramazza [29] provides a simple and heuristic method to capture the meaning of natural language. In addition, the traditional multi-criteria approach assumes that decision factors are independent. In other words, the aggregation of performance value is additive based on the independent relationship among decision factors. However, the interdependence among various factors is common in real world. To reflect this reality, fuzzy measures [72,47]—or more generally, non-additive set functions—can be used [73]. Therefore, a nonlinear integral i.e., Choquet integral, or so-called non-additive fuzzy integral, is recommended in place of the traditional weighted average methods [73].

Consequently, this study intends to construct a systematic performance measurement framework based on hierarchical balanced scorecard (HBSC) for ERP and adopts fuzzy linguistic variables incorporating with non-additive fuzzy integral to deal with the ambiguity and vagueness existing in evaluators' subjective judgments in order to reflect the subjectivity, uncertainty, and interaction embedded in the HBSC framework and the process of performance evaluation. Specifically, the findings would enable decision-makers and managers to better understand the performance of ERP implementation and, more generally, would contribute to the understanding of the performance level and strategic decision of high-tech firms implementing ERP systems. Using the balanced scorecard dimensions, high-tech firms can also assess their relative performance after ERP implementation, the results of which can then be used to understand and monitor how performance affects strategic decision-making.

This paper is now organized as follows: Section 2 reviews the literature on ERP performance; Section 3 derives the ERP performance criteria to respond to BSC perspectives; Section 4 constructs the hierarchical balanced scorecard framework for ERP performance measurement; Section 5 elaborates on the linguistic variables, fuzzy measures, and non-additive integral employed in this study; Section 6 uses the proposed method to assess the ERP performance of high-tech firms; and finally, the results and conclusions are presented in Section 7.

2. Review of the relevant ERP and performance literature

2.1. The implementation of ERP

Various studies have been conducted to identify critical factors affecting the successful implementation of ERP. Many focus on individual case studies and industry surveys, and have covered a broad range of research issues. Motwani et al. [46] applied a case study methodology to compare a successful and unsuccessful ERP implementation, finding that the main factors behind a successful implementation consisted of cautious, evolutionary, bureaucratic implementations backed by careful change management, network relationships, and cultural readiness. Yen and Sheu [79] also used case study method involving direct observation and systematic interviews to examine five US and Taiwanese manufacturing firms, the results of which indicated that ERP implementation should be aligned with a firm's competitive strategy. Meanwhile, Ash and Burn [2] expressed their concerns with ERP implementation by using embedded, multiple case studies to investigate the complex phenomenon of an e-ERP project. Umble et al. [67] pointed out a new set of key issues for successful ERP implementation, which was also considered by Sun et al. [63]. They studied ERP implementation in 26 firms and used five critical success factors, with a total of 22 attributes, in a simulation model to assess strategic ERP implementation. Mabert et al. [41] surveyed 193 manufacturing firms in the US and pointed out that successful ERP implementation depended on the organization's size, motivation, implementation strategies, the modules and functionalities implemented, and operational benefits. Ehie and Madsen [22] also adopted an empirical study surveying 36 manufacturing companies in the Midwestern region of the US, identifying the critical issues affecting ERP implementation as project management principles, human resource development, business process re-engineering, cost/budget issues, IT infrastructure, consulting services, and top management support. Given such a range of perspectives, though, it is unlikely that a consensus on a final definition of ERP implementation can be achieved.

2.2. The benefits of ERP

Another research theme focuses on the details of implementing ERP and their related success and benefit. Chand et al. [8] pointed out that implementing an ERP system not only increased customer satisfaction and reduced operational costs but also eventually resulted in increased profits and growth of an organization. Furthermore, Davenport [17] and Markus et al. [42] indicated that the benefits of an ERP system were related to process productivity improvement, reduced error, and timely availability of consistent information. They also suggested that ERP benefits should be measured from different perspectives. Trimmer et al. [64] reported that support for the continuing use of critical success factors helped focus on the benefits of ERP in rural healthcare. Al-Mashari et al. [1], on the other hand, argued that ERP benefits could be realized when a close connection is established between the implementation approach and business process performance measures. Shang and Seddon [56], in fact, proposed a comprehensive framework for assessing ERP benefits at five dimensional levels: operational, managerial, strategic, IT infrastructural, and organizational. Meanwhile, Murphy and Simon [48] examined the intangible benefits and demonstrated how they could be incorporated into traditional evaluation methods (e.g., cost-benefit analysis) of ERP implementation. Most of these studies conducted empirical surveys or case studies to examine the extent of, and the different factors affecting, ERP implementation, rather than constructing multiple, comprehensive aspects to understanding the benefits of ERP.

2.3. The performance of ERP

Up to now, a quite few literatures focus on the post-implementation ERP system performance evaluation. Only some of articles literatures discussed the impact of ERP systems on the productivity and performance. Dehning and Richardson [19] proposed a generic framework to guide the development of an ERP performance measurement model. Based on a comprehensive review of financial accounting and finance literature on IT performance measurement, their framework classified these existing studies according to five paths. Meanwhile, Hunton et al. [32] examined the longitudinal impact of ERP adoption on firm performance and found that return on assets, return on investment, and asset turnover significantly improved over a 3-year period. Matolcsy et al. [43] conducted an empirical study with publicly available financial accounting data to analyze ERP adoption on overall firm and business process performance. They also found that the ERP adoption led to sustained operational efficiencies, increased profitability, improvements in accounts receivable management, and improved overall liquidity. In addition, Law and Ngai [38] conducted an empirical study to investigate the success of ERP adoption, the results of which indicated the positive associations between the perceptions of ERP success and improvement in business processes and perceived organizational performance.

On the other hand, Klaus et al. [35] integrated historical analysis, a meta-analysis of representative IS literature, and a survey of academic experts to investigate ERP implementation. Their studies addressed the complex question of how to assess the organizational benefits derived from an ERP system. Similarly, to examine how an ERP system is expected to affect a specific firm's performance, the work of Poston and Grabski [50] indicated a significant improvement in a firm's performance after the implementation of its ERP system. Hitt et al. [30] also claimed that ERP deployment had a significant, measurable effect on a firm's performance. Nicolaou et al. [49] compared financial data from firms adopting enterprise information systems with that from a matched control group. The results of their univariate analysis of performance across time periods demonstrated that firms adopting enterprise systems had a significantly higher differential performance in the second year after implementation than the control group. Finally, Wang et al. [71] examined 300 firms from Taiwan's top 500 largest corporations and found that a cohesive ERP project team had a significantly positive effect on overall team performance in the context of ERP implementation.

Although the aforementioned literature reveals ambiguity in evaluating and predicting whether ERP implementation has a significant impact on a firm's performance, these empirical studies do demonstrate that ERP systems do deliver improved firm performance; for example, increased customer satisfaction, increased productivity, and reduced financial cycles. However, a comprehensive and systematic approach to measure ERP system performance is necessary, since both its implementation and performance measurement are typically complex and difficult to assess. To address this dilemma, this study develops a performance measurement system for high-tech firms based on the balanced scorecard framework and a rigid mathematical approach.

2.4. The performance measurement of ERP systems

The business environment is characterized by a high level of uncertainty, thus the process of ERP system assessment involves numerous problems [74]. Because ERP implementation is a complex and uncertain project, firms that are successful in its implementation need to carefully examine all related factors to increase operational efficiency. Markus et al. [42] suggested that the ERP implementation was an enormously complex undertaking for organizations. ERP systems can affect nearly every aspect of organizational performance and function, and measures for the success of ERP systems should reflect this fact. Indeed, Richardson [19] argued that a one-dimensional approach fails to explain information technology (IT) performance. Hence, an ERP system evaluation framework must consider multiple aspects and criteria to facilitate performance measurement against a firm's strategies. Performance measurement in this context is therefore an integrated holistic and systematic concept. It needs to embody the whole organizational strategy and capture tangible and intangible aspects, cover qualitative and quantitative criteria, and include aspects of synergy through integrating useful information.

Although ERP systems have been recognized as a useful infrastructure for many businesses integrating functional information systems, as well as information flows and business processes, typical implementation is quite complex. Existing ERP systems cannot evaluate the performance of every process in an organization. Thus, no single performance measurement approach or tool can provide ERP system performance evaluation following implementation over a period of time. Constructing a systematic and holistic performance framework to assess ERP implementation is therefore essential to subsequent decision-making. Evaluators frequently adopt the common ERP evaluation criteria as performance indicators without developing any that include cross-function and cross-functional measurement. However, this study addresses this issue by analyzing the results of a survey of firms that have implemented ERP systems. More specifically, it adopts the balanced scorecard (BSC) as an ERP performance measurement approach and proposes an accessible model for ERP performance measurement tools, whereby the criteria that influence performance, as well as the model itself, offer a methodology to assess the performance of different ERP implementations. In this context, the BSC and non-additive fuzzy set theory approaches have the potential to produce an innovative evaluation method for ERP performance, which solves the existing difficulties. The literature related to the performance evaluation of ERP is quite scarce. Most focused mainly on case studies or adopted qualitative techniques to analyze the success or failure of ERP implementation, rather than designing and developing systematic approaches to evaluate ERP performance. This research aims to address this gap by providing a current understanding of ERP implementation performance measurement and the consequent strategic objectives. In particular, this study seeks to understand the performance evaluation issues with ERP system implementation, by expanding on the existing approaches to and literature on performance measurement of and management approaches to ERP implementation in decision-making activities.

3. Derivation of a balanced scorecard for ERP performance measurement

Chand et al. [8] proposed an improved tool named the ERP scorecard, which integrates Kaplan and Norton's balanced scorecard with Zuboff's automate, informate, and transformate goals for evaluating the performance of ERP systems. They suggested that the BSC framework could be an appropriate approach for the performance measurement of ERP implementations. However, the questions of how to measure the performance of ERP and what kinds of methodology for appropriately measuring post-implementation ERP performance. Specifically, there is a lack of an analytic framework and a rigidity approach for ERP performance measurement in the existing literature. The BSC infrastructure can serve as a guide to identifying measures for evaluating the performance and strategic objectives of ERP systems, though. Up to now, only Chand et al. [8] have attempted to employ this approach, through case studies, in assessing the specific strategic impacts of ERP systems. However, a well-defined framework and approach to building ERP balanced scorecards is needed, aligning ERP implementation and operation with strategic objectives through a series of quantifiable performance measurement indicators.

Before ERP implementation, there is no way to directly measure and monitor the exact performance level of ERP commercial packages following their implementation. In fact, the complexity of ERP systems makes it difficult for a single aspect or indicator to assess the multiple perspectives of ERP implementation performance measurement. Dehning and Richardson [19] argued that a one-dimensional approach failed to explain information technology (IT) performance. Consequently, a firm planning to implement an ERP system must employ multiple evaluation criteria from different performance perspectives. ERP system performance measurement can thus be viewed as a multiple criteria decision-making (MCDM) problem. Moreover, Farbey et al. [23] argued that IT managers often used simplistic, estimative quantitative factors only, as they were often unable to capture many of the expected qualitative and intangible indicators. Remenyi and Sherwood-Smith [53] and Davern and Kauffman [18] presented a similar argument that information systems were not easily assessed, especially when it involved intangibles. One way to interpret both tangible and intangible factors affecting information system performance, though, is to employ the balanced scorecard (BSC), within which are embedded relevant tangible and intangible performance indicators. Kaplan and Norton [33] emphasized that the BSC was only a template and must be customized for the specific elements of a sector, organization, or industry. The BSC provides the quantitative and qualitative basis to a complex decision-making process in which high-tech firms need to measure ERP performance against multiple criteria. The original BSC, developed for performance measurement by Kaplan and Norton [33], employed performance metrics from financial, customer and internal business processes, and learning and growth perspectives. Thus, it linked financial and non-financial perspectives into an integrated performance measurement system, aligning organizational goals and other traditional functions with corporate strategy by means of leading indicators (performance driver-oriented indicators) and lagging indicators (outcome-based indicators) to monitor strategy implementation. Kaplan and Norton [83] indicated that the original BSC turned business strategies into measurable indicators. BSC provided a series of performance measurement indicators that could be utilized to guide strategic direction and objectives.

ERP performance evaluation should also consider the direct impact from factors such as organizational processes, customers' perspectives, and information integration. Evaluators usually consider common measurement criteria, making judgments based on the comprehensive framework of ERP performance. The primary objective of the BSC in this study, however, is to identify and define the core set of performance measures that will enable managers to understand the current state of the ERP system in order to monitor its future performance. Moreover, ERP performance measurement needs a comprehensive framework that systematically guides the identification and evaluation of ERP performance measures. Thus, an ERP balanced scorecard framework in this study will guide the identification and evaluation of critical ERP performance measures. A well-defined framework also helps decision-makers/managers to re-examine the goals of ERP in their organization.

Based on the above discussion, this study highlights the relevance of developing a systematic and holistic model, which involves internal business processes, and organizational, financial, and non-financial factors, to measure ERP performance in an organization. Therefore, all the dependent and interactive perspectives related to the process of ERP performance evaluation must be considered in order to attain strategic success. These criteria are in accordance with most ERP systems and must be integrated within a hierarchical balanced scorecard (HBSC) framework for ERP performance evaluation. With this purpose, this study develops such a hierarchical framework and combines precise quantitative approaches to explain, understand, and identify the direct and indirect contributions of ERP implementation. Once the ERP balanced scorecard framework has been defined, it will guide the identification of the required indicators for ERP performance measurement.

Keeney and Raiffa [34] proposed five principles that must be followed when formulating criteria: (1) completeness, the criteria must cover all important aspects of the decision-making problem; (2) operational, the criteria must be meaningful for decision-making analysis; (3) decomposable, the criteria can be broken down from a higher to a lower hierarchy to simplify the evaluation; (4) nonredundant, there must be no double counting of criteria; and (5) minimum size, the number of criteria should be as few as is feasible. To ensure the validity and reliability of the BSC-based ERP performance measurement framework and its corresponding criteria, this study reviewed multiple sources of information. First, the four dimensions of the evaluation criteria with which to assess ERP performance were extracted from the literature. Second, six experts were consulted about the critical ERP performance concerns that needed to be addressed during the measurement of ERP performance. Particularly, the performance measurement of intangible benefits of ERP systems needs to rely on qualitative information yielded by experts, which is one of common applications in the field of decision making [11]. This in-depth interview with six experts ensured the performance indicators to meet the five principles. Thus, the ideal experts have to be familiar with the benefits of ERP systems, the implementation of ERP, ERP processes, and performance assessment. As mentioned in this manuscript, this study interviewed three academic experts in information management and three industry experts with over 6 years' experience in the information sector of high-tech industry. The academic experts who dedicated to the field of ERP helped assess the completeness, decomposability, and nonredundancy of the performance indicators through their domain knowledge. The information sector of high-tech companies in Taiwan is actually responsible for implementing and maintaining ERP as well as information systems. Therefore, the three industry experts who have adequate experience in ERP implementation and processes helped assess the performance indicators to meet completeness, operationality, and minimum size. Although the criteria varied, it converged on the four dimensions of the BSC-based ERP performance evaluation framework (see Fig. 1). The framework constructed in this study involves both the intangible and tangible criteria of ERP performance measurement. In addition, based on Kaplan and Norton [83], each evaluation category, consisting of 4–7 indicators, is appropriate for performance measurement. Based on these principles, this study developed a framework that provides a comprehensive and objective performance measurement mechanism. The four dimensions of the BSC-based ERP performance measurement system are as follows:

(1) Financial perspective: the goal of the ERP system here is to reduce costs and improve return on investment (ROI). Chand et al. [8] suggested that the financial performance indicators include reduction of computer operating costs, reduction of business operating and administrative expenses, and reduction in inventory costs and stock outs. Ranganathan and Brown [52] reported that ERP systems with greater functional scope or greater physical scope result in positive and higher returns. Because an ERP investment implies a firm's commitment to improve business processes [44] and increase business integration [3]. Due to the improved business integration benefited from ERP systems, the investment of a firm results in higher returns [52]. Therefore, increased return on investment is regarded as a financial indicator of ERP systems. In addition, the improved business processes leads to improved overall productivity [59]. Additionally, one of the objectives of an ERP implementation may be to standardize processes and centralize the control over information. To reach this objective, firms have to standardize their IT systems, which may improve the operational effectiveness and efficiency and reduce operational costs [1]. Thus, reduction of IT operational costs is considered a performance indicator in financial perspective to evaluate the performance of ERP systems. Moreover, the customer relationship management incorporated into ERP systems was evidenced to increase market share [54] and sales growth rate [27,54], thanks to the implementation of ERP leading to quick reaction to market opportunities [1]. Therefore, increased market share and sales growth rate should be considered the

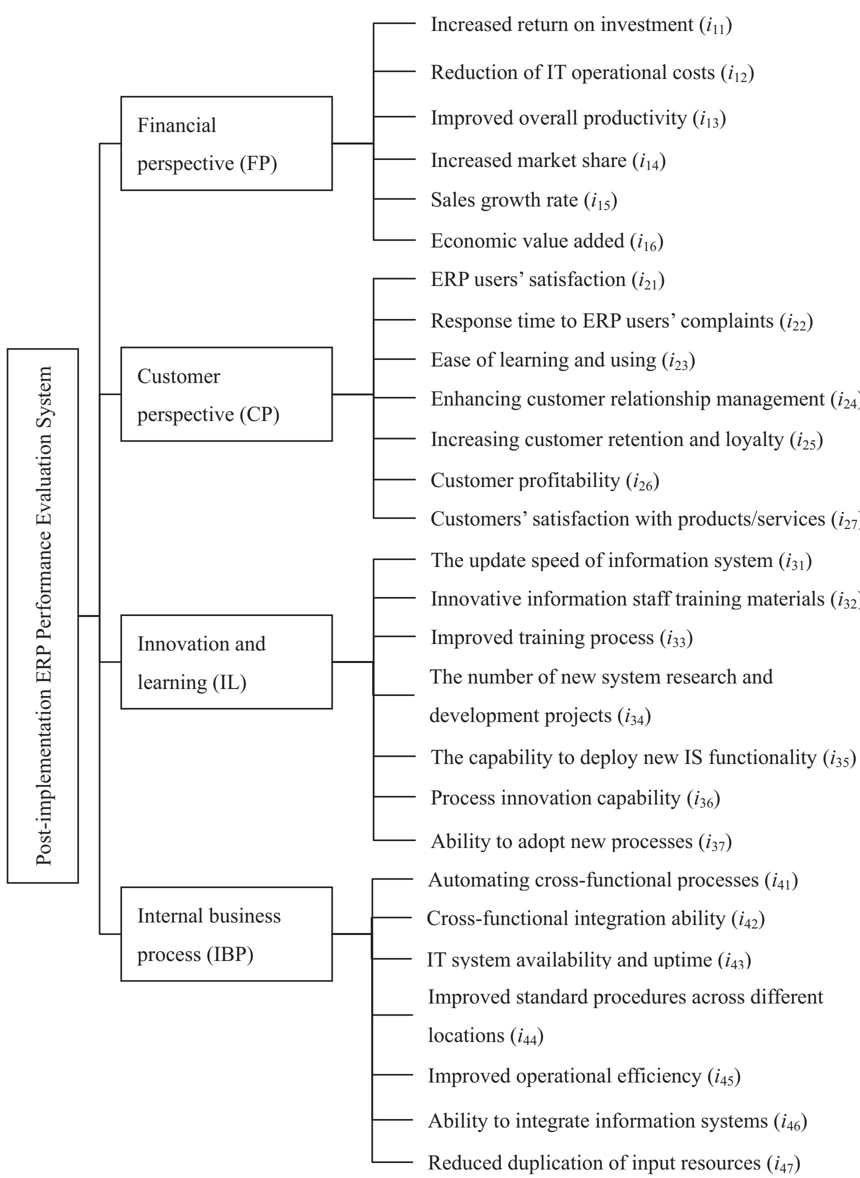

Fig. 1. HBSC performance measurement system for post-implementation.

financial performance indicators to measure the ERP systems. Finally, [77] reported a significant relationship existed between ERP implementation and economic value added, based on the antecedent empirical evidences that ERP systems resulted in positive financial performance of firms.

(2) Customer perspective: the main functions of ERP implementation are to meet customer needs more effectively and eventually increase customer satisfaction. The successful implementation of ERP systems relies on the dedication of ultimate users in companies. Thus, ERP users' satisfaction [75], response time to ERP users' complaints [75], and the ease of learning and using [45] should be included as the performance indicators in customer perspective. In addition, since meeting customer needs and satisfying customers are the main functions of ERP implementation, enhancing customer relationship management [54], customer retention and loyalty [54], customer profitability [27], and customers' satisfaction with products and services [75] are considered the performance indicators in customer perspective.

(3) Innovation and learning perspective: the goal of the ERP system here is to give employees the capability to learn and use the system. Thus, the quality and effectiveness of the training programs affects employees' ability to not only use the new system but also modify process operations. Wu and Wang [75] indicated that the successful implementation of ERP systems relied on user satisfaction. ERP vendors could provide timely support to update the systems [7,57,20] and training [51] to improve the user satisfaction. Hence, the update speed of the information [51], innovative information staff training materials [51], and improved training process [51] could serve as performance indicators in customer perspective. Additionally, Srivardhana and Pawlowski [58] suggested that ERP systems had positive impacts on business process innovation. To enable business process innovation through ERP systems, companies need to evaluate the number of new system research and development projects offered by ERP suppliers or implementation teams [58], the ability of ERP suppliers or implementation teams to deploy new information system functionality [26], the process innovation capability of ERP systems [58], and the capability of ERP systems to adopt new innovation process [58]. Thus, this study views the number of new system research and development projects, the capability to deploy new IS functionality, process innovation capability, and the ability to adopt new innovation processes as performance indicators in innovation and learning perspective.

(4) Internal business process: one of the widely discussed issues is the need for an ERP process fit for business and process changes. Improving access to information on ERP systems across different functions could make some strategic decisions more operationally and tactically effective. Davenport [17] also suggested that ERP implementation is often performed alongside business process re-engineering, and so improving business process efficiency is one of the important tasks for an ERP system. The internal business process covers a reduced rate of input errors, increased efficiency of business processes, and improved decision support [8]. Therefore, automating cross-functional processes [8], cross-functional integration ability [8,69], improved standard procedures across different locations [8], reduce input resources [8], ability to integrate information systems [1], improved operational efficiency [8,4], and IT system availability and uptime [56] are regarded as performance indicators in the perspective of internal business process, based on the characteristics intrinsic in the intangible benefits of ERP systems [1].

This section has introduced a BSC-based ERP performance measurement framework based on a literature review and expert consensus for constructing an assessment model for post-implementation ERP performance evaluation. The next section presents the hierarchical balanced scorecard (HBSC) ERP performance measurement system and the methodology for performance measurement.

4. HBSC and ERP performance methodology

The hierarchical structure provides insight and landscape into performance measurement system for a well-defined performance metric through a number of indicators. In addition, the hierarchical structure has many characteristics, including top management controlling the execution of performance, the scope and relationship among different strategic objectives, and the framework whereby the performance metric can be transformed into measurable criteria. Within this structure, every level has an objective, for example, four strategic objectives are deployed the overall performance evaluation of the ERP system. Therefore, a hierarchical structure is a necessity for ERP performance measurement.

The hierarchical structure adopted in this study to measure the post-implementation ERP performance in high-tech firms is shown in Fig. 1. As mentioned, the four BSC-based dimensions were derived from a comprehensive literature review and consultation with experts, confirming the appropriateness of the 27 critical criteria. All participants agreed that the evaluation criteria should be comprehensive and relevant to assessing post-implementation ERP performance. Furthermore, the five principles for selecting criteria suggested by Keeney and Raiffa [34] and that for selecting performance indicators proposed by Kaplan and Norton [33] were used to formulate the hierarchy for post-implementation ERP performance measurement in high-tech firms. Consequently, this study constructed a HBSC with three levels. The first level is the goal level, the ultimate goal of the evaluation being to determine the overall performance of the post-implementation ERP system. The second level is the strategic objective, which includes financial perspective, customer perspective, innovation and learning perspective, and internal business process. The third level is the criteria level, which includes 27 evaluation criteria. It should be noted that the inner dependence among the criteria, suggested by the experts, exists within the four perspectives.

A BSC-based ERP system with a well-defined performance hierarchy and appropriate evaluation processes guarantees more correct results and facilitates faster assessments for decision-makers. Decisions based on correct performance information may lead to more efficient and effective management of firms and adjustments in strategic objectives.

5. Methodology

The balanced scorecard provides an understanding of top management's strategy and translates this into a series of strategic objectives with operational measures at lower levels, such as measurable performance criteria. This study proposes a method of ERP performance evaluation that draws on the knowledge and experience of experts who understand how performance level achieves the minimum requirements and how strategy is revised in a management control setting, through complex performance evaluation processes. However, these processes in different domains depend on experts' personal experience, knowledge, background, situations, and state of mind, and they may have only a vague perception about the degree of preference for one option over another, and so cannot apply a precise value to their preferences. Chen et al. [11] indicated that the evaluation using judgments from experts is one of common applications in the field of decision making. On the other hand, conventional qualitative criteria are too complex, or too ill-defined, to be measured numerically. Therefore, it is more appropriate to present their preferences by means of linguistic variables rather than crisp ones [81,82]. Fuzzy logic can enhance the efficiency of measurements based on approximate reasoning algorithms and vague information. Therefore, considering the fuzziness in the evaluation data and performance measurement process, linguistic variables are used to determine the degree of importance for all criteria and assess the performance values of firms. Fuzzy linguistic variables enable the vagueness and uncertainty of both qualitative, subjective, imprecise data and human cognitive analysis of the criteria to be conducted from the evaluation process. Wang et al. [84] also indicated that the linguistic variable composed by triangular fuzzy numbers was able to reduce experts' subjective judgments. Because the interval of triangular fuzzy numbers depends on experts' professional ability to the extent that the surveyed experts can clearly distinguishes the difference of decision criteria [84].

Furthermore, it is usually assumed that the criteria are independent and additive in multi-criterion decision-making; hence, the weighted average method is often applied to aggregate the importance weight of those criteria [66]. Also, one may argue that traditional multi-attribute decision-making (MADM) methods, such as analytic hierarchy process (AHP) and simple additive weighting (SAW), are able to evaluate the importance of criteria and aggregate the overall importance. However, these assumptions are not always true of many real world situations [66,76], as illustrated by the BSC proposed by Kaplan and Norton [33] that emphasizes the cause-and-effect relationship among different performance indicators. Ignoring the effects of such interdependency could lead to assessment bias and ineffective decisions [37]. In other words, the fuzziness and vagueness embedded in human perceptions and the interdependence among decision factors coexist in the process of performance measurement. To cope with these challenges, some studies have adopted methods based on BSC dimensions, which are able to address the ambiguities or reflect the interdependent relationships. For example, Huang et al. [31] assessed the performance of knowledge management by using the BSC-based analytic network process (ANP). Tseng [65] integrated fuzzy set theory, ANP, and decision-making trial and evaluation laboratory (DEMATEL) to determine the relative weight of each BSC-based performance indicator. Bhattacharya et al. [6] applied fuzzy ANP to construct a BSC-based performance measurement framework for the green supply chain. Shaik and Abdul-Kader [55] integrated BSC and DEMATEL into a comprehensive performance measurement model to assess reverse logistics enterprises, which demonstrated the causal-effect interactions among decision factors. Nevertheless, these studies did not attempt to aggregate the performance information from different alternatives for comparison. To take account of interdependence and aggregate data from various decision factors, Sugeno [61] therefore proposed the fuzzy integral method, which applied fuzzy measures [5] to the problems of addressing the effects of interdependency. The results of fuzzy measures can be further applied to assess the performance of relevant alternatives [60], providing an alternative computational scheme for aggregating information [13]. Unlike the traditional, additive assessment methods, which do not consider the effects of interdependency between the criteria [37] and adhere to the notion that the importance of two criteria in a probability framework is nothing more than the sum of the importance of the individual criteria, fuzzy measures are more flexible in accepting that there are greater or lower values than simply the sum of the importance of multiple criteria. In other words, the fuzzy integral method allows the modeling of interactions between criteria [25]. Applying linguistic variables, the non-additive fuzzy integral approach enables researchers to account for the vague and imprecise semantics and the interdependence among criteria, so reducing the problems of subjective judgments involved in decision support. Several studies have adopted this method in performance evaluations [14,40,70], and this study also attempts to apply the non-additive fuzzy integral and fuzzy linguistic variables—as described in the following subsections—to assess different high-tech firms' post-implementation ERP performance, based on the BSC perspectives.

5.1. Determining the degree of importance of criteria and the performance values of firms

In the performance evaluation process, strategic objectives are set according to the available data and information, which are vague, imprecise, and uncertain by nature. To address this issue, fuzzy linguistic variables are capable of handling the vagueness and uncertainty of data and information. Fuzzy linguistic variables represent those values that are presented as words and sentences in human or artificial language. In this study, fuzzy numbers represent both the decision-maker's subjective assessment of the degree of importance of the criteria and the performance value of the firms' ERP according to those criteria. Herrera et al. [28] and Chen et al. [10] suggested seven-point linguistic scales for quantifying human's verbal judgments to achieve tractability, robustness, and better rapport with reality. Wang et al. [70] suggested that the interval of triangular fuzzy numbers should be determined by the surveyed experts' consensus. Based on this manner, this study adopted a seven-point linguistic scale and then consulted the experts who are the same objects surveyed in this study to objectively determine the interval values. The seven triangular fuzzy numbers were used to describe the linguistic performance terms, according to a type of conversion scale: very poor (VP), poor (P), median poor (MP), fair (F), median good (MG), good (G), very good (VG); with the corresponding fuzzy numbers as (0.0, 0.0, 0.1), (0.0, 0.15, 0.3), (0.2, 0.3, 0.4), (0.3, 0.5, 0.7), (0.6, 0.7, 0.8), (0.7, 0.85, 1.0), (0.9, 1.0, 1.0), respectively (see Fig. 2).

During the overall ERP performance evaluation, evaluators' perceptions of the criteria vary in terms of the degree of their importance and performance values, which are reflected by the values of the linguistic variables. Given that m represents the evaluators, their evaluations of importance and performance are expressed as $\tilde{p}_i, i = 1, 2, \cdots, m$. One way to integrate the linguistic variable expressing decision makers' evaluations of importance is to apply the fuzzy arithmetic proposed by [21]. Thus, the aggregation of importance and performance values determined by m decision makers is presented by three vertices of triangular fuzzy numbers, as seen in Equation 1:

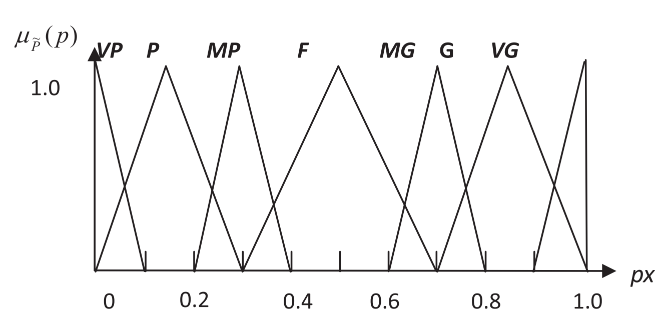

Fig. 2. Membership functions for seven performance values.

$$\bar{\bar{P}}_{ij} = ({}_{L}\bar{p}_{i}j,\ {}_{M}\bar{p}_{ij},\ {}_{R}\bar{p}_{ij}) = \left(\left(\frac{\sum_{p=1}^{m} p_{ij}^{p})}{m}, \left(\frac{\sum_{p=1}^{m} p_{ij}^{p})}{m}, \left(\frac{\sum_{p=1}^{m} p_{ij}^{p})}{m}\right)\right. \quad (1)$$

where $\bar{\bar{P}}_{ij} = ({}_{L}\bar{p}_{i}j,\ {}_{M}\bar{p}_{ij},\ {}_{R}\bar{p}_{ij})$ are triangular fuzzy numbers representing their points in the left, middle, and right positions, and ${}_{L}\overline{P}_{ij}$, ${}_{M}\overline{P}_{ij}$, and ${}_{R}\overline{P}_{ij}$ indicate the importance of dimension i and criterion j.

However, the fuzzy numbers for the importance weights of decision factors need to be converted into crisp numbers to be of subsequent use. Many defuzzification methods have been developed, including center of sum, center of gravity, mean of maxima, and α-cut. The defuzzification method proposed by Chen and Klein [9], though, is a highly sensitive and effective approach, whereby the precise importance value can be obtained and further incorporated into the fuzzy integral to aggregate the overall performance of alternatives. Chen and Klein [9] employed a method utilizing fuzzy subtraction of a referential rectangle ($\tilde{R}$; here, considered as a fuzzy number) from a fuzzy number ($\tilde{X}$); the rectangle is derived from multiplying the height of the membership function of $\tilde{X}$ by the distance between the two crisp maximizing and minimizing barriers. Equation 2 shows how this fuzzy subtraction can be performed at level α_i:

$$\begin{aligned}\tilde{X}_{\alpha_i} <-> \tilde{R} &= [l_i,\ r_i][-][c,\ d] \\ &= [l_i - d,\ r_i - c], \quad i = 0, 1, 2, \cdots \infty \end{aligned} \quad (2)$$

where $<->$ and $[-]$ represent fuzzy subtraction and interval subtraction operators, respectively; l_i and r_i denote the left and right loci of $\tilde{R}$, and c and d, the left and right barriers. The defuzzification rating of the fuzzy number can be obtained with Eq. (3):

$$D(\tilde{X}) = \frac{\sum_{i=0}^{n} r_i - c}{\sum_{i=0}^{n}(r_i - c) - \sum_{i=0}^{n}(l_i - d)}, \quad n \to \infty \quad (3)$$

where n denotes the number of α-cuts; as n approaches ∞, the sum is the measured area. In Eq. (3), $\sum_{i=0}^{n}(r_i - c)$ is positive, $\sum_{i=1}^{n}(l_i - d)$ is negative, and $0 \le D(\tilde{X}) \le 1$, if $0 \le x \le 1$.

5.2. The λ-fuzzy measure and non-additive fuzzy integral

An important aspect in building real applications for multiple criteria decision-making or performance measurement is the interactive relationship among the feature criteria towards the strategic objective. In this study, such interaction exists in both the HBSC framework and the feature criteria. Fuzzy measures and fuzzy integrals are versatile operators that can be used in many different domains for decision-making or evaluation, under the assumption of interaction within the framework: criteria are not always independent of each other in a real ERP performance evaluation process. Thus, fuzzy measures can be employed to examine the interdependent relationships between the criteria [12], which, along with the fuzzy integral, was the method employed in this study to analyze the ERP performance and specify the interrelationship among the four dimensions of the HBSC framework. The fuzzy measure is used with the fuzzy integral to aggregate information, and can be defined as the subjective importance of a criterion during the evaluation process. Sugeno and Terano [62] incorporated the λ-additive axiom to simplify this aggregation. In the fuzzy measure space $(\mathbf{X},\ \beta,\ g)$, let $\lambda \in (-1,\ \infty)$. If $A \in \beta$, $B \in \beta$, $A \cap B = \phi$, then the fuzzy measure g is λ-additive. This particular fuzzy measure is called the λ-fuzzy measure, because it has to satisfy λ additively, and is also known as the Sugeno measure [61].

Assuming that $\mathbf{X} = \{x_1,\ x_2, \ldots,\ x_n\}$ and $P(\mathbf{X})$ is the power set of $\mathbf{X}$, the set function g: $P(X) \to [0, 1]$ is a fuzzy measure, which is non-additive and preserves the following properties: $\forall A,\ B \in \beta(\mathbf{X})$, $A \cap B = \phi$, and $g_\lambda(A \cup B) = g_\lambda(A) + g_\lambda(B) + \lambda g_\lambda(A) g_\lambda(B)$ for $-1 < \lambda < \infty$. To differentiate this measure from other fuzzy measures, g_λ denotes the λ-fuzzy measure. When $\lambda \ne 0$, the λ-fuzzy measure g is non-additive; otherwise, $\lambda = 0$ means that the λ-fuzzy measure g is additive and there is no interaction between decision factors [36]. Additionally, the λ-fuzzy measure of the finite set can be derived from fuzzy densities, as indicated in Eq. (4) [34,39]:

$$\begin{aligned} g_\lambda(\{x_1,\ x_2,\ \ldots,\ x_n\}) &= \sum_{i=1}^{n} g_i + \lambda \sum_{i_1=1}^{n-1} \sum_{i_2=i_1+1}^{n} g_{i_1} g_{i_2} + \cdots \\ &+ \lambda^{n-1} g_1 g_2, \ldots, g_n \\ &= \frac{1}{\lambda} |\prod_{i=1}^{n}(1 + \lambda g_i) - 1| \text{ for } -1 < \lambda < \infty \end{aligned} \quad (4)$$

Based on the boundary conditions in Eq. (4), $g_\lambda(\mathbf{X}) = 1$, λ can be determined via Eq. (5):

$$\lambda + 1 = \prod_{i=1}^{n}(1 + \lambda g_i) \quad (5)$$

In the fuzzy measure space $(\mathbf{X},\ \beta,\ g)$, let h denote a measurable function from $\mathbf{X}$ to $[0, 1]$. The fuzzy integral of h over A with respect to g is then defined as

$$\int_A h(x) dg = \sup_{\alpha \in [0,1]} [\alpha \wedge g(A \cap F_\alpha)] \quad (6)$$

where $F_\alpha = \{x | h(x) \ge \alpha\}$ [73] and A represents the domain of a fuzzy integral. When $A = X$, the fuzzy integral can be presented as $\int hdg$. For simplicity, consider the fuzzy measure g of $(\mathbf{X},\ P(\mathbf{X}))$ where $\mathbf{X}$ is a finite set. Let $h : \mathbf{X} \to [0, 1]$ and assume, without loss of generality, that the function $h(x_i)$ is monotonically decreasing in i, for instance $h(x_1) \ge h(x_2) \ge \cdots \ge h(x_n)$. To ensure that the elements in $\mathbf{X}$ are renumbered, we use Eq. (7):

$$\int h(x) g = \bigvee_{i=1}^{n} [h(x_i) \wedge g(H_i)] \quad (7)$$

where $H_i = \{x_1,\ x_2,\ \ldots,\ x_n\}$, and $i = 1, 2, \ldots, n$. In practice, h can be regarded as a given alternative's performance on a particular decision factor, and g represents the subjective degree of importance for each decision factor. The non-additive fuzzy integral of $h(x)$ with respect to g gives the overall assessment of the attribute. To simplify the calculation, the same fuzzy measure of the Choquet integral is expressed as Eq. (8):

$$\begin{aligned} (C) \int hdg &= h(x_n) g(H_n) + [h(x_{n-1}) - h(x_n)] g(H_{n-1}) + \cdots \\ &+ [h(x_1) - h(x_2)] g(H_1) \\ &= \mathrm{h}(x_n)[\mathrm{g}(H_n) - \mathrm{g}(H_{n-1})] \\ &+ \mathrm{h}(x_{n-1})[\mathrm{g}(H_{n-1}) - \mathrm{g}(H_{n-2})] + \cdots + \mathrm{h}(x_1) g(H_1) \end{aligned} \quad (8)$$

where $0 \le h(x_1) \le h(x_2) \le \cdots \le h(x_n) \le 1$, $H_1 = \{x_1\}$, $H_2 = \{x_1, x_2\}, \ldots,$ $H_n = \{x_1,\ x_2,\ \ldots,\ x_n\} = \mathbf{X}$. In the literature, the fuzzy integral defined by $\int hdg$ is termed a non-additive fuzzy integral, and denotes the overall performance of the alternatives.

6. An empirical study: post-implementation ERP performance measurement

The optimality of the generated evaluation depends significantly upon domain experts and their professional knowledge and experiences in adopting ERP systems. Generally, evaluation is a procedure for determining the value of objects based on the values of their attributes. Evaluators assign linguistic values to fuzzy variables in terms of given numerical (measurement) values. This section presents the data collection process and the results of the empirical analysis. In addition, a worked example is provided in Appendix to illustrate the calculation process.

6.1. Data collection

Researchers emailed the checklist of ERP performance measures to senior managers and senior auditors of high-tech firms to determine the overall ERP implementation performance. These were considered ideal respondents, because being responsible for a firm's strategy, managers have a good understanding of the internal/external operations of the business; while auditors are responsible for monitoring whether the internal management processes comply with required standards. Furthermore, as both IS managers and technology staff are responsible for ensuring data integrity and appropriate data-processing within ERP systems, the HBSC is mainly designed to provide them with an overview for evaluating organizational performance [24].

The samples for this study were taken from those high-tech firms that had implemented ERP systems over the last 3 years (i.e., SAP, Oracle, Baan, JDEdwards, SSA, and so on). The hierarchical BSC dimensions shown in Fig. 1 were then developed to measure each firm's ERP performance and its impact on strategic objectives. As already mentioned, six senior managers and six auditors—with more than 10 years' work experience on average—per firm were asked to complete the survey from six different high-tech firms.

6.2. Determining the degree of importance of performance indicators

In the non-additive fuzzy integral method, the weighting of decision factors starts from the bottom level of the decision hierarchy. In the hierarchical structure, every item comprises an answer to a question and its associated degree of importance, and during the survey process, the importance of criteria is weighted by using the fuzzy number. First, the three academic and three industry experts as survey respondents evaluated the importance of the performance indicators on a questionnaire. Then these values were converted into triangular fuzzy numbers by using the linguistic variables shown in Fig. 2. The performance indicators were subsequently weighted by aggregating the respondents' evaluation values with Eq. (1), which were finally entered into Eq. (3) to calculate the degree of importance for each; the results are shown in Table 1. As can be seen, the Innovation and Learning Perspective has the highest rank, with a weighting of 0.870, followed by Financial Perspective, 0.776, Customer Perspective, 0.745, and lastly Internal Business Process, 0.531. Within each performance perspective, the weighting for each performance indicator similarly represents their degree of importance. The highest ranking of 0.870 was shared between the three indicators of Update Speed of Information System, Innovative Information Staff Training Materials and Improved Training Process.

6.3. Aggregating the performance values of high-tech firms' ERP systems

Based on the importance weightings from the HBSC for post-implementation ERP systems, 72 senior IS managers and auditors from 6 different high-tech firms evaluated the performance of their ERP systems. As already described, the respondents' evaluation values were aggregated as fuzzy performance values by using Equation 1 and converted into crisp numbers by using Eq. (3). The λ-value of each performance perspective was calculated by using Eq. (5) with a corresponding density measure,

Table 1
Weighting of 4 performance perspectives and 27 performance indicators.

Perspective	Weight ($g_i(\cdot)$)	Indicator	Weight ($g_i(\cdot)$)
Financial perspective (FP)	0.776	Increased return on investment (i_{11})	0.620
		Reduction of IT operational costs (i_{12})	0.647
		Improved overall productivity (i_{13})	0.870
		Increased market share (i_{14})	0.620
		Sales growth rate (i_{15})	0.647
		Economic value added (i_{16})	0.604
Customer perspective (CP)	0.745	ERP users' satisfaction (i_{21})	0.800
		Response time to ERP users' complaints (i_{22})	0.776
		Ease of learning and using (i_{23})	0.673
		Enhancing customer relationship management (i_{24})	0.723
		Increasing customer retention and loyalty (i_{25})	0.720
		Customer profitability (i_{26})	0.537
		Customers' satisfaction with products/services (i_{27})	0.694
Innovation and learning (IL)	0.870	Update speed of information system (i_{31})	0.870
		Innovative information staff training materials (i_{32})	0.870
		Improved training process (i_{33})	0.870
		The number of new system research and development projects (i_{34})	0.750
		The capability to deploy new IS functionality (i_{35})	0.844
		Process innovation capability (i_{36})	0.783
		Ability to adopt new processes (i_{37})	0.776
Internal business process (IBP)	0.531	Automating cross-functional processes (i_{41})	0.500
		Cross-functional integration ability (i_{42})	0.540
		IT system availability and uptime (i_{43})	0.647
		Improved standard procedures across different locations (i_{44})	0.423
		Improved operational efficiency (i_{45})	0.540
		Ability to integrate information systems (i_{46})	0.667
		Reduced duplication of input resources (i_{47})	0.700

Table 2
Fuzzy measure and aggregated value for Company A.

Perspective	Indicator	$h(\cdot)$	$g_i(\cdot)$	$g_\lambda(\cdot)$		$(c)\int h(\cdot)dg_\lambda(\cdot)$ (λ-value)
FP	i_{11}	0.769	0.620	$g_\lambda(i_{12})$	0.647	0.845 (−0.999)
	i_{12}	0.909	0.647	$g_\lambda(i_{12},i_{11})$	0.866	
	i_{13}	0.667	0.870	$g_\lambda(i_{14}, i_{11}, i_{16})$	0.948	
	i_{14}	0.500	0.620	$g_\lambda(i_{14}, i_{11}, i_{16}, i_{13})$	0.994	
	i_{15}	0.500	0.647	$g_\lambda(i_{14}, i_{11}, i_{16}, i_{13}, i_{12})$	0.999	
	i_{16}	0.667	0.604	$g_\lambda(i_{14}, i_{11}, i_{15}, i_{16}, i_{12}, i_{13})$	1.000	
CP	i_{21}	0.667	0.800	$g_\lambda(i_{27})$	0.694	0.761 (−0.999)
	i_{22}	0.500	0.776	$g_\lambda(i_{27}, i_{24})$	0.916	
	i_{23}	0.667	0.673	$g_\lambda(i_{27}, i_{24}, x_{26})$	0.962	
	i_{24}	0.769	0.723	$g_\lambda(i_{27}, i_{24}, i_{26}, i_{25})$	0.990	
	i_{25}	0.667	0.720	$g_\lambda(i_{27}, i_{24}, i_{26}, i_{25}, i_{23})$	0.997	
	i_{26}	0.667	0.537	$g_\lambda(i_{27}, i_{24}, i_{26}, i_{25}, i_{23}, i_{21})$	1.000	
	i_{27}	0.769	0.694	$g_\lambda(i_{27}, i_{24}, i_{26}, i_{25}, i_{23}, i_{21}, i_{22})$	1.001	
IL	i_{31}	0.667	0.870	$g_\lambda(i_{36})$	0.783	0.767 (−0.999)
	i_{32}	0.769	0.870	$g_\lambda(i_{36}, i_{32})$	0.972	
	i_{33}	0.667	0.870	$g_\lambda(i_{36}, i_{32}, i_{37})$	0.995	
	x_{34}	0.500	0.750	$g_\lambda(i_{36}, i_{32}, i_{37}, i_{35})$	1.000	
	i_{35}	0.667	0.844	$g_\lambda(i_{36}, i_{32}, i_{37}, i_{35}, i_{33})$	1.001	
	i_{36}	0.769	0.783	$g_\lambda(i_{36}, i_{32}, i_{37}, i_{35}, i_{33}, i_{31})$	1.001	
	i_{37}	0.667	0.776	$g_\lambda(i_{36}, i_{32}, i_{37}, i_{35}, i_{33}, i_{31}, i_{34})$	1.001	
IBP	i_{41}	0.500	0.500	$g_\lambda(i_{47})$	0.700	0.733 (−0.998)
	i_{42}	0.500	0.540	$g_\lambda(i_{47}, i_{46})$	0.901	
	i_{43}	0.667	0.647	$g_\lambda(i_{47}, i_{46}, i_{43})$	0.966	
	i_{44}	0.500	0.423	$g_\lambda(i_{47}, i_{46}, i_{43}, i_{45})$	0.985	
	i_{45}	0.500	0.540	$g_\lambda(i_{47}, i_{46}, i_{43}, i_{45}, i_{44})$	0.992	
	i_{46}	0.667	0.667	$g_\lambda(i_{47}, i_{46}, i_{43}, i_{45}, i_{44}, i_{42})$	0.998	
	i_{47}	0.769	0.700	$g_\lambda(i_{47}, i_{46}, i_{43}, i_{45}, i_{44}, i_{42}, i_{41})$	1.000	

g_i, to represent the importance weighting of each indicator. Finally, the Choquet integral value and λ-value for the overall performance of one company was calculated by using Eq. (8).

Table 2 shows the fuzzy measure and aggregated value for one of the six high-tech firms, Company A—a fictitious name used for confidentiality reasons. The fourth column, $g_i(\cdot)$, in Table 2, repeats the importance weightings for performance indicators from the fourth column in Table 1. The crisp performance value, $h(\cdot)$, in the third column in Table 2, shows Company A's performance on each indicator, while the λ-value in the fifth column presents the fuzzy measure, and the Choquet integral value $()c\int h(\cdot)dg_\lambda$ in the last column represents the evaluators' perception of the overall performance. As can be seen, the Financial Perspective has the highest Choquet integral value of 0.845, which indicates that Company A performs best in the Financial Perspective, according to the judgment of the evaluators. Moreover, a λ-value so close to -1 means that there is complete dependence and mutual influence relationships among indicators.

The Choquet integral value of each performance perspective can be further aggregated to determine the overall performance of Company A. Table 3 repeats Company A's performance on each perspective from the $h(\cdot)$ column and the importance weightings for each perspective from the $g_i(\cdot)$ column in Table 2. By then applying Eqs. (5) and (8), the fuzzy measure, λ-value of $g_\lambda(\cdot)$, and the Choquet integral value, $()c\int h(\cdot)dg_\lambda$, can be respectively calculated. The Choquet integral value of 0.826 represents the overall performance of Company A.

Applying the same calculation process to the remaining five high-tech companies, their overall ERP system performance values are shown in Table 4. The results show that Company E has the highest performance value (0.870), followed by Company B (0.857), F (0.830), A (0.826), D (0.753), and C (0.675). According to the BSC dimensions therefore, Company E shows the best ERP post-implementation performance.

7. Conclusion

This study attempts to represent the performance of ERP systems in the post-implementation stage as a measurement standard for high-tech firms. In this final section, the value and contribution of the BSC-based ERP performance measurement system in this attempt will be summarized.

First, this study develops an innovative approach by applying the non-additive fuzzy integral to incorporate the BSC dimensions. Its contribution lies in proposing a comprehensive ERP performance measurement standard that takes account of individual performance indicators when analyzing the four BSC dimensions for each high-tech firm. This study then continues and extends the research on operational ERP performance measurement at firm level and develops an industry-specific algorithm to effectively measure the performance of ERP implementation.

Second, numerous factors that affect ERP performance are embedded in the balanced scorecard, which can thus increase both the precision of ERP performance measurement and the

Table 3
Fuzzy measure and overall performance value for Company A.

Company	Perspective	$h(\cdot)$	$g_i(\cdot)$	$g_\lambda(\cdot)$		$(c)\int h(\cdot)dg_\lambda(\cdot)$ (λ-value)
A	FP	0.845	0.776	$g_\lambda(P_{FP})$	0.776	0.826 (−0.998)
	CP	0.761	0.745	$g_\lambda(P_{FP}, P_{IL})$	0.972	
	IL	0.767	0.870	$g_\lambda(P_{FP}, P_{IL}, P_{CP})$	0.994	
	IBP	0.733	0.531	$g_\lambda(P_{FP}, P_{IL}, P_{CP}, P_{IBP})$	1.000	

Table 4
High-tech companies' ERP system performance values and rankings.

Company	Performance value	Ranking
A	0.826	4
B	0.857	2
C	0.675	6
D	0.753	5
E	0.870	1
F	0.830	3

effectiveness of the subsequent decision-making on the successful implementation of an ERP system.

Third, this study quantifies ERP performance measurement in a manner that is comparable across high-tech firms to improve the companies' ERP performance against the benchmark in the industry, and also extends the existing approaches to ERP performance measurement and strategic decision-making by considering a series of critical factors. It therefore contributes to that body of studies attempting to investigate ERP system performance at firm level.

In addition, the ERP performance measurement framework employed in this study provides a platform for further investigation into how different perspectives affect the performance of ERP systems, which is closely linked to strategic objectives. Finally, this study presents an evaluation approach that can act as a reference for better understanding the factors that affect ERP performance.

Moreover, one may argue that traditional MADM methods could be applied under an interdependent, uncertain, and fuzzy environment. Thus, it is suggested to compare traditional MADM methods and non-additive fuzzy integral to clarify the impacts to different results led by different basic assumptions.

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Appendix

The calculation process was described as follows. First, the respondents evaluated the importance of performance indicators and the performance of their ERP systems according to the set of indicators presented in the HBSC framework as presented in Fig. 1. Their evaluation values were converted into triangular fuzzy numbers by using the linguistic variables shown in Fig. 2. Three academic experts in information management and three industry experts with over 6 years' experience in the information sector of high-tech industry were asked to evaluate the importance of performance indicators in the HBSC. Take the weighting of Automating Cross-functional Processes (i_{41}) for example, the six experts' evaluation was presented as the following Table 5.

Table 5
The triangular fuzzy number of respondents on i_{41}.

Respondent	Linguistic performance	Triangular fuzzy number
Expert A1	F	(0.3, 0.5, 0.7)
Expert A2	F	(0.3, 0.5, 0.7)
Expert A3	F	(0.3, 0.5, 0.7)
Expert I1	MP	(0.2, 0.3, 0.4)
Expert I2	MG	(0.6, 0.7, 0.8)
Expert I3	F	(0.3, 0.5, 0.7)

Second, the triangular fuzzy numbers of six respondents were aggregated by using Eq. (1) as follows:

$$\bar{\tilde{P}}_{41} = \left(\frac{0.3+0.3+0.3+0.2+0.6+0.3}{6}, \frac{0.5+0.5+0.5+0.3+0.7+0.5}{6}, \frac{0.7+0.7+0.7+0.4+0.8+0.7}{6}\right) = (0.333, 0.500, 0.667)$$

Third, the aggregated triangular fuzzy number of i_{41} was defuzzied by using Eq. (3) to obtain the weight of i_{41}:

$$\mathrm{D}(\tilde{X}) = \frac{(0.667-0)+(0.500-0)}{[(0.667-0)+(0.500-0)]-[(0.333-1)+(0.500-1)]}$$
$$= 0.500$$

With the same procedure, the weights of four performance perspectives and indicators can be derived and presented as $g_i(\cdot)$ in Table 1.

In the fourth step, this study evaluated the performance of ERP systems from six different high-tech companies according to the HBSC framework. Six senior managers and six auditors per company were asked to evaluate their ERP systems. The performance of ERP systems from six companies was evaluated on the performance indicators in HBSC with the same linguistic variable employed in step 1. Then, repeat the same step from 1 through 3 to obtain the performance values on every indicators. The performance values on the 27 indicators were shown as $h(\cdot)$ in Table 2.

In the fifth step, the g_i values of each sub-indicator in Internal Business Process were input into Eq. (5) to derive the λ-value:

$$\lambda + 1 = (1 + 0.500\lambda)$$
$$\times (1+0.540\lambda)\times(1+0.647\lambda)\times(1+0.423\lambda)\times(1+0.540\lambda)\times(1+0.667\lambda)\times(1+0.700\lambda)$$

This calculation was conducted by applying Mathematica 9.0. The λ-value was -0.998 and presented in Table 2. The λ-values of other three dimensions were obtained with the same procedure.

The λ-fuzzy measures were aggregated by using Eq. (4) in the sixth step. To derive the λ-fuzzy measure value for firm A, the calculation started from the indicator with highest h_i value in Internal Business Process, i.e., Reduced Duplication of Input Resources (i_{47}), to the indicator with lowest h_i value, i.e., Automating Cross-functional Processes (i_{41}). The λ-fuzzy measure value for i_{47} was derived with Eq. (4) and shown as follows:

$$g_\lambda(i_{47}) = 0.7$$

Then, the indicator with highest h_i (i_{47}) was aggregated with the indicator with second highest h_i, i.e., Ability to Integrate Information Systems (i_{46}):

$$g_\lambda(i_{47}, i_{46}) = 0.7 + 0.667 + (-0.998) \times 0.7 \times 0.667 = 0.901$$

The aggregated fuzzy integral value was then aggregated with the indicator with third highest h_i, i.e., IT system availability and uptime (i_{43}):

$$g_\lambda(i_{47}, i_{46}, i_{43}) = 0.901 + 0.647 + (-0.998) \times 0.901 \times 0.647$$
$$= 0.966$$

Then, repeat the same procedure in this step until the indicator with lowest h_i value.

Finally, the Choquet integral value was calculated by using Eq. (8) to aggregate the overall performance of ERP systems from the bottom level of hierarchical framework for firm A. The calculation of Choquet integral value of International Business Process was shown as follows:

$$(c)\int h(\cdot)\mathrm{d}g = 0.5\times 1 + (0.5-0.5)\times 0.998$$
$$+(0.5-0.5)\times 0.992 + (0.5-0.5)\times 0.985 + (0.667-0.5)\times 0.966 + (0.667-0.667)\times 0.901 + (0.769-0.667)\times 0.7$$
$$= 0.733$$

Repeat the same procedure in this step, the Choquet integral value of other three perspectives can be derived. With the same process from the first through the last step, the Choquet integral value which represents the overall ERP system performance of six companies can be derived as presented in Table 4.

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