

Cloud computing decision-making using a fuzzy AHP approach

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ABSTRACT

The increasing number of cloud service users renders it critical for firms to select cloud service suppliers that suit all company business strategies and goals. From the literature review, we found a lack of research addressing the interdependence of decision criteria. In this study, we address this crucial research gap by presenting an integrative research model that combines fuzzy logic theory and the analysis hierarchy process (AHP). We use this model to holistically evaluate cloud providers focused on PaaS and IaaS with predetermined criteria. The simulation results reveal a correlation between decision criteria, and cloud provider performance is found to vary considerably.

Keywords: Cloud computing, fuzzy logic, interdependence, Spearman's rank correlation, AHP.

RÉSUMÉ

Du fait d'un nombre de plus en plus important d'utilisateurs de services de cloud, la question cruciale qui se pose est celle d'une sélection appropriée d'un fournisseur cloud qui réponde aux stratégies commerciales et aux objectifs de l'entreprise. L'une des préoccupations des utilisateurs réside dans le manque de travaux de recherche portant sur l'analyse de l'interdépendance des critères de décision. Dans cette étude, nous abordons cette lacune essentielle en développant un modèle de recherche intégré qui combine la théorie de la logique floue et le processus d'analyse hiérarchique. Le modèle développé a été utilisé pour évaluer globalement les fournisseurs de cloud PaaS et IaaS, sur la base de critères prédéterminés. Les résultats de la simulation ont indiqué une corrélation entre les critères de décision et les performances des fournisseurs de cloud, qui varient considérablement.

Mots-clés : Cloud computing, la logique floue, interdépendance, corrélation de rang de Spearman, AHP.

1. INTRODUCTION

Cloud computing is used as a solution that creates a virtual space for infrastructure, platforms, and software (Pépin, 2013). It has acquired considerable popularity primarily owing to its ease of use. As a result, several providers, including Amazon, Microsoft and Google, have begun to offer this form of technology. According to an analysis by Gartner¹, cloud computing usage is still growing and will account for the bulk of new IT expenditures by 2016. The most generally accepted definition of cloud computing is provided by the National Institute of Standards and Technology (Mell and Grance, 2001): “*Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction. This cloud model is composed of five essential characteristics, three service models, and four deployment models.*”

1.1. Research background

Cloud computing is primarily described as a model based on virtualization technology and pay-per-use pricing models (Jula *et al.*, 2014). It can manage three layers:

Infrastructure as a Service (IaaS) programs serve as environments for

deploying, running and managing virtual machines and storage products. Technically speaking, IaaS programs offer incremental computing resource scalability (scale up and down) and on-demand storage. In a cloud infrastructure, a user or company client is the master of his virtual environment and can install whatever he sees fit (e.g., virtual servers) configured on demand, making it possible to execute an application. The most representative IaaS products include Amazon EC2, Google Compute Engine and Rackspace.

Platform as a Service (PaaS) systems serve as platforms for developing additional applications, (e.g., the Google App Engine (GAE)). Whereas IaaS systems are primarily concerned with production and operations, PaaS systems are concerned with providing two levels of service: development platforms and applications that provide superior services. PaaS systems allow developers to create frameworks adapted to their development needs. Compared to flourishing SaaS products, PaaS products are more concise. Well known products include Force.com, Google App Engine and Windows Azure Platform.

Software as a Service (SaaS) products provide access to complete applications (e.g., customer relationship management (CRM)). Such products often take the form of application catalogs that are accessible to users. In a model SaaS product, the application is already complete and operational; the focus is not on development but on prefer-

¹ Source: <http://www.gartner.com/newsroom/id/3188817>

ences. For a company, model SaaS cloud products may prove particularly instrumental during prototyping as they allow users, with a short delay and reduced costs, to evaluate solutions without using their own resources. SaaS products were developed before PaaS and IaaS systems were created. Furthermore, related costs of development are very low, and thus in the current market, SaaS products are rich in both in quantity and sophistication. There are a variety of classic products, with the most representative being Google Apps, Salesforce CRM, and Office Web Apps.

Thus, a key challenge that businesses face when evaluating cloud computing services involves selecting those services best suited to their various business needs.

1.2. Research framework

Design science seeks to develop technologically-based solutions to important and relevant business problems (Hevner *et al.*, 2004). Amandine Pascal identifies three design-science research cycles—the relevance, design, and rigor cycles—and decision criteria for effective design research (Pascal, 2012). In the present study, we aim to design a decision-making model for selecting appropriate cloud providers from the perspective of design science based on previous studies.

Design is both a process (set of activities) and a product (artifact). March and Smith (1995) identify two design processes and four design artifacts produced via design-science research in IS. The two processes involve building

and evaluating, and artifacts include constructs, models, methods, and instantiations. Our design is based on these two design processes and four design artifacts. During the first phase of our study, evaluation criteria on providers were determined. During the second phase, a fuzzy AHP method was used to select the most appropriate providers. Finally, we describe the feasibility of the method.

Based on the Publication Schema for a Design Science Research Study (Gregor and Hevner, 2013), we have divided this paper into six sections. The remainder of the paper is organized as follows. A literature review and analysis are given in the following section. Section 3 describes the structure of the decision model for cloud supplier selection. Section 4 evaluates and analyzes the model in greater detail. Finally, a discussion and conclusion are outlined in sections 5 and 6, respectively. This article contributes a framework that allows cloud users to compare cloud services and that allows cloud suppliers to gradually improve their services. Such a systematic methodology for comparing and rating cloud providers can generate healthy competition between cloud providers.

2. LITERATURE REVIEW AND ANALYSIS

Cloud computing represents a new means of outsourcing IT resources. For SaaS products, outsourced resources are application software; for IaaS products, outsourced resources are computing hardware (e.g., servers, storage devices); and for PaaS products, out-

sourced resources include hardware, development and software hosting platforms. Through a literature review, Stefanie Leimeister found that cloud computing is primarily described as an IT outsourcing model on the basis of virtualization technologies (Leimeister *et al.*, 2010). Benedikt Martens and Frank Teuteberg described cloud computing and IT outsourcing using the same decision model and showed that both provide similar benefits to their users; methods developed for IT outsourcing can also be applied to analyses of cloud computing (Martens *et al.*, 2012). To summarize, the literature on IT outsourcing decisions serves as a background for our research on cloud computing.

Cloud computing research is still in its early stages. Much of the existing literature focuses on benefits and risks associated with cloud computing, on organizational case studies of cloud adoption, and on cloud-computing architecture (Bhattacharjee and Park, 2014). A methodological approach to the comparison of cloud solutions vs. in-house solutions has been proposed based on the direct economic effects of migration on the cloud (Naldi and Mastroeni, 2014). This approach is based on the use of net present values and stochastic models for storage prices and memory needs. The adoption of new technologies (e.g., cloud computing) is a complex phenomenon that is highly ambiguous and that presents a variety of opportunities and challenges (Luoma and Nyberg, 2011). We conducted a detailed analysis of cloud-related decision criteria and decision models. The identified articles are summarized in Table 1.

2.1. Research gaps & research questions

During earlier stages of cloud computing development, the primary focus was on technical factors; now, the focus is gradually moving towards a business perspective (Hoberg *et al.*, 2012; Son and Lee, 2011). Recently, the number of companies that have adopted cloud computing services has increased. Furthermore, cloud-experienced companies are confronted with various challenges as they must compare several alternatives based on incomplete decision criteria (Martens *et al.*, 2012).

Numerous research results indicate that decisions involved in selecting cloud suppliers have become increasingly important (Aissaoui *et al.*, 2007; Li and Wan, 2014). However, cloud provider selection has become a key issue due to the limited transparency of existing cloud services (Godse and Mulik, 2009). It is often difficult to judge the quality of cloud services and to make a decision (Martens *et al.*, 2012). In essence, the selection of top suppliers is always a difficult task for decision-makers due to the growth of cloud computing and owing to the fact that various criteria (e.g., cost and performance) must be considered during the decision-making process. Therefore, cloud customers are faced with the challenge of identifying providers that can satisfy their requirements.

Despite the theoretical and practical need to understand dynamics of appropriate fit between a company and its cloud services providers, this issue has been infrequently studied. Although most existing studies assume

Reference	Factor	Approach	Evaluation
(Ghodsypour and Brien, 1998)	Cost, on-time delivery, quality, capacity	LP and AHP	Simulation
(Verma and Pullman, 1998)	Cost, quality, flexibility (agility), on-time delivery, delivery lead time	DCA	Simulation
(Yang and Huang, 2000)	Cost, strategy, quality, technology, management	AHP	Simulation
(de Almeida, 2001)	Cost, risk	MAUT	Simulation
(de Almeida, 2007)	Cost, dependability, on-time delivery	ELECTRE and MAUT	Simulation
(Araz <i>et al.</i> , 2007)	Cost, capacity, quality, flexibility, on-time delivery	FGP and PROMETHEE	Case study
(Yang <i>et al.</i> , 2007)	Cost, capacity, risk, quality	AHP	Simulation
(Cao et Wang, 2007)	Cost, quality	Not mentioned	Simulation
(Wang et Yang, 2007)	Cost, resource, strategy, risk, management, quality	AHP and PROMETHEE	Simulation
(Wang <i>et al.</i> , 2008)	Cost, risk, quality, environment, strategy	AHP and ELECTRE	Simulation
(Chen and Wang, 2009)	Quality, technology, capacity, flexibility	FV	Simulation
(Li <i>et al.</i> , 2010)	Cost, capacity, quality, response time	Not mentioned	Case study
(Martens and Teuteberg, 2012)	Cost, risk	LP	Simulation
(Martens <i>et al.</i> , 2012)	Cost	TCO	Case study
(Tajdini and Nazari, 2012)	Cost, political, technology, strategy	AHP	Case study
(Hsu and Liou, 2013)	Cost, on-time delivery, risk, compatibility, quality, flexibility	DEMATEL and ANP	Case study
(Li and Wan, 2014)	Cost, quality, technology, flexibility, on-time delivery	FLP	Case study
(Garg <i>et al.</i> , 2013)	Cost, agility, accountability, performance, assurance, security, usability	AHP	Simulation
(Godse and Mulik, 2009)	Cost, vendor reputation, architecture, functionality, usability	AHP	Case study
(Ye <i>et al.</i> , 2012)	Cost, response time, throughput	Optimization	Simulation
(Menzel and Ranjan, 2012)	Cost, benefits, opportunities, risk	ANP	Simulation

Table 1. Decision Factors and Approaches

that service attributes are independent of one another, in reality, attributes are interdependent (Saripalli and Pingali, 2011). Interdependent relationships between selection criteria are critical to rational decision-making. Based on these gaps in existing research, we seek to address the following research questions:

RQ1: Which attributes drive cloud provider selection?

RQ2: How is the value of each attribute determined?

RQ3: Are selected attributes interdependent?

RQ4: Which algorithm should be applied for ranking purposes?

2.2. Identification of criteria

This section shows that the existing cloud-research literature presents a number of partial explanations for factors that affect cloud provider selection. What is missing is an integrated view; such a view would be valuable. This paper contributes to this important topic by synthesizing numerous existing studies and identifying factors to include in and exclude from the model.

Generally speaking, cloud provider selection processes are shaped by various factors. Relevant cloud provider selection criteria presented in previous studies are shown in Table 1. This section synthesizes this literature and presents a preliminary test of a model of key factors that reflect cloud provider selection. We also explain why various features of the model contribute to cloud provider selection.

Table 1 shows that most researchers agree that various criteria are relevant when selecting a vendor. Generally speaking, security and reliability constitute critical challenges for users (Géczy *et al.*, 2012; Koehler *et al.*, 2010). Additionally, when using cloud services, it is important to properly manage data and to ensure that a provider offers appropriate support. Nevertheless, costs constitute a relevant decision criterion during provider selection, and agility concerns have been highlighted as the most significant benefit of cloud computing service adoption. Our decision model thus includes four principal factors: cost, risk, agility and quality.

2.3. Decision-making methods

Although several methods of decision-making support exist (multi-attribute utility theory (MAUT) and the preference ranking organization method for enrichment evaluations (PROMETHEE)), the AHP is the most popular method due to its user friendliness and effectiveness (Lee *et al.*, 2012).

Analysis hierarchy process (AHP). Saaty developed the AHP model in 1990 to create a systematic approach to solving multi-criteria decision problems (Saaty, 1990). Decision makers can use the AHP to identify priorities and to make structured comparisons between different providers in selecting the most appropriate one (Tam and Tummala, 2001). Additionally, because of its user friendliness and systematic support in identifying and prioritizing relevant criteria, the AHP is easy to apply (Ishizaka, 2014).

When formulating an AHP model, a hierarchical structure can allow individuals or groups of individuals to systematically visualize a problem in terms of relevant criteria and sub-criteria (Tam and Tummala, 2001). Elements of this hierarchy can be divided into groups and are compared pairwise on each hierarchy level. The results are translated into corresponding pairwise comparison judgment matrices, and the eigenvector with the highest eigenvalue is identified. A disadvantage of this approach lies in the fact that the number of pairwise comparisons can become very large (more specifically: $n(n-1)/2$).

Analytic network process (ANP). The ANP is an extension of the AHP, and it offers solutions to problems that cannot be structured hierarchically. In an ANP network, criteria and alternatives are arranged in clusters rather than in layers. Arrows between the clusters denote effects among criteria and alternatives. The ANP has become a popular method due to its capacity to manage relationships between decision factors and alternatives.

Multi-attribute utility theory (MAUT). Unlike the AHP, which focuses on the relative importance of decision criteria through pairwise comparisons, MAUT is based on utility functions. A utility function quantifies the preferences of a decision-maker and aggregates several of a decision-maker's degrees of satisfaction with a particular criterion. However, utility functions are difficult to derive. Rather, numerous utility questions must be posed, and such functions are too subjective as utility levels may change across users.

Fuzzy logic. Appropriate decisions are difficult to make in an uncertain environment when vagueness factors are not considered. Fuzzy set theory addresses this issue by considering the ambiguous nature of decision-making problems (Zadeh, 1965). A fuzzy set is defined by a membership function through which elements are mapped to a certain interval $([0, 1])$. A value of zero shows that an element does not belong to a set, whereas a value of one reflects the complete membership of an element to a set. Other values in the described interval denote a specific degree of membership to a set. Finally, a closeness coefficient for each alternative is defined to rank all alternatives.

Total cost of ownership (TCO). TCO-based models for supplier choice primarily involve the summarization and quantification of all or several costs associated with the choice of vendors (de Boer *et al.*, 2001). This method and philosophy extends beyond purchasing prices to include several other purchase-related costs. TCO models are further classified by usage, i.e., vendor selection and vendor evaluation. TCO models are limited in that they consider only one decision-factor cost.

Optimization-based approaches for cloud service selection. In the field of service selection, optimization is defined as "finding the most suitable services for clients or providers and thereby maximizing or minimizing one or several criteria while still adhering to the constraints."

Elimination and Choice Translating Reality (ELECTRE). ELECTRE belongs to a family of outranking methods, which form another category of MCDM

methods. It assesses candidates in terms of each criterion and identifies the degree of dominance of one candidate over another. MAUT and outranking methods mainly differ in that the former identifies the best choice, whereas the latter identifies a shortlist of alternatives. The approach can address several conflicting performance criteria. The ELECTRE method is advantageous in that users can conduct another MCDA based on a restricted set of alternatives, thus saving a considerable amount of time.

Preference ranking organization method for enrichment evaluation (PROMETHEE). The PROMETHEE does not offer structuring capabilities. In cases involving several criteria (more than seven), it may be very difficult for a decision maker to obtain a clear understanding of a problem and to evaluate results. The PROMETHEE offers no specific guidelines on weight determination. In addition, generalized criteria must be defined, and this may pose a challenge for inexperienced users.

Decision-making trial and evaluation laboratory (DEMATEL). The DEMATEL has been widely used to extract complex problem structures. The DEMATEL allows users to quantitatively extract interrelationships between multiple factors included in a problem.

Linear programming (LP). Linear programming can be employed to analyze several different areas of life. It serves as a good approach to solving complex problems and is flexible. However, as not all variables are linear, final solutions are often limited and

unrealistic expectations arise as a result.

Discrete choice analysis (DCA). Past research in econometrics, marketing, and in other social sciences shows that DCA serves as an effective methodology for analyzing choices made in complex decision-making situations (e.g., supplier selection). Discrete choice analyses serve as a systematic approach to identifying the relative weights of attributes that a decision maker trades off when making a selection from a possible set of alternatives. This approach is based on the multinomial logit (MNL) econometric model, which uses a maximum likelihood estimation scheme to maximize the probability of an alternative's selection based on given attribute levels.

The multinomial logit model is limited in three key ways: it cannot represent random taste variations, it presents restrictive substitution patterns, and it cannot be used with panel data when unobserved factors are correlated over time for each decision maker.

Conclusion. All the above approaches present unique advantages and limitations. Identifying such advantages and limitations is instrumental to the preparation of an efficient ranking system. The purpose of service ranking is to help users evaluate and compare different services so that they can select the most appropriate services that meet their requirements.

The key factors that are of relevance to provider selection are presented in Table 1. As is shown, the AHP has been the most common approach used in recent years. However, this approach cannot capture the subjectivity

(or fuzziness) of human judgments as verbal assessments are converted into crisp values. Meanwhile, fuzzy logic cannot measure the consistency of judgments provided by a decision maker. The fuzzy analytic hierarchy process (FAHP) constitutes a merger of the two methods that inherits the advantages of both and that therefore addresses the above mentioned problems.

3. FUZZY AHP DECISION MODEL

3.1. Model description

The fuzzy AHP decision-making approach to supplier selection is based on the multi-criteria AHP decision-making method and on fuzzy set theory. The AHP allows one to derive ratio scales from paired comparisons. Using

the AHP, expert opinions and evaluations can be integrated, and a complex problem can be devised into a simple hierarchical system with higher and lower levels. In this work, the AHP is used to calculate weights of each decision factor.

Provider selection often occurs in a fuzzy environment. For example, demand changes occur from one period to another with a probability distribution that is difficult to estimate due to a lack of historic data. Therefore, demand must be characterized as a fuzzy variable. In our decision model, fuzzy set theory is used to rank cloud services. This merger of two methods differs from approaches employed in previous FAHP methods (extent analysis and fuzzy preference programming). As our numerical simulation is based on real datasets, we do not need experts to assess the performance of each supplier.

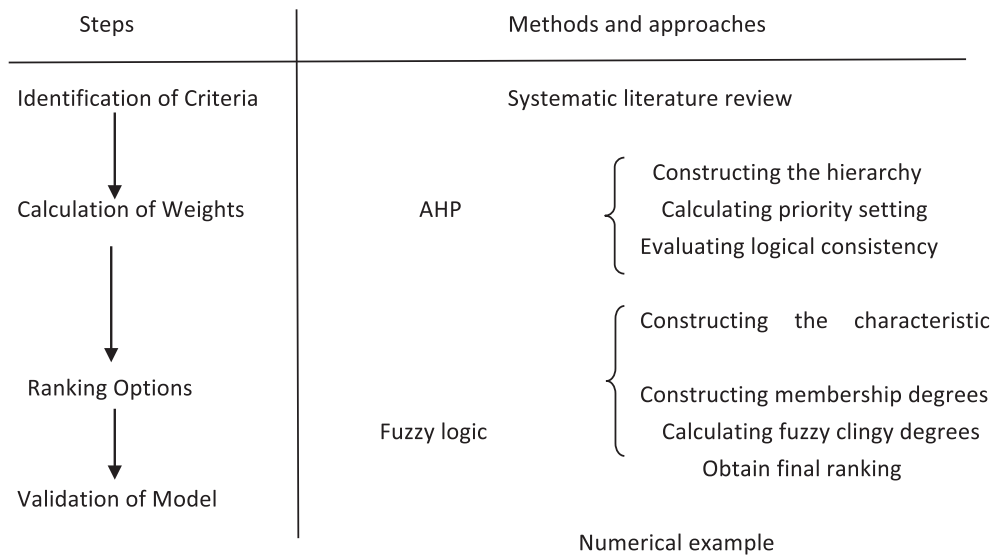


Figure 1. Model description

3.2. Hierarchy construction

A complex decision-making problem is structured and decomposed into sub-problems (e.g., sub-objectives, criteria, and alternatives) within a hierarchy. We consider sub-criteria for each main factor.

Cost - The first question that arises before shifting to cloud computing concerns whether cloud computing is cost effective. Our model makes basic distinctions between cost-oriented factors (service, adoption, allocation and agency costs). Agency costs are incurred via monitoring and perfor-

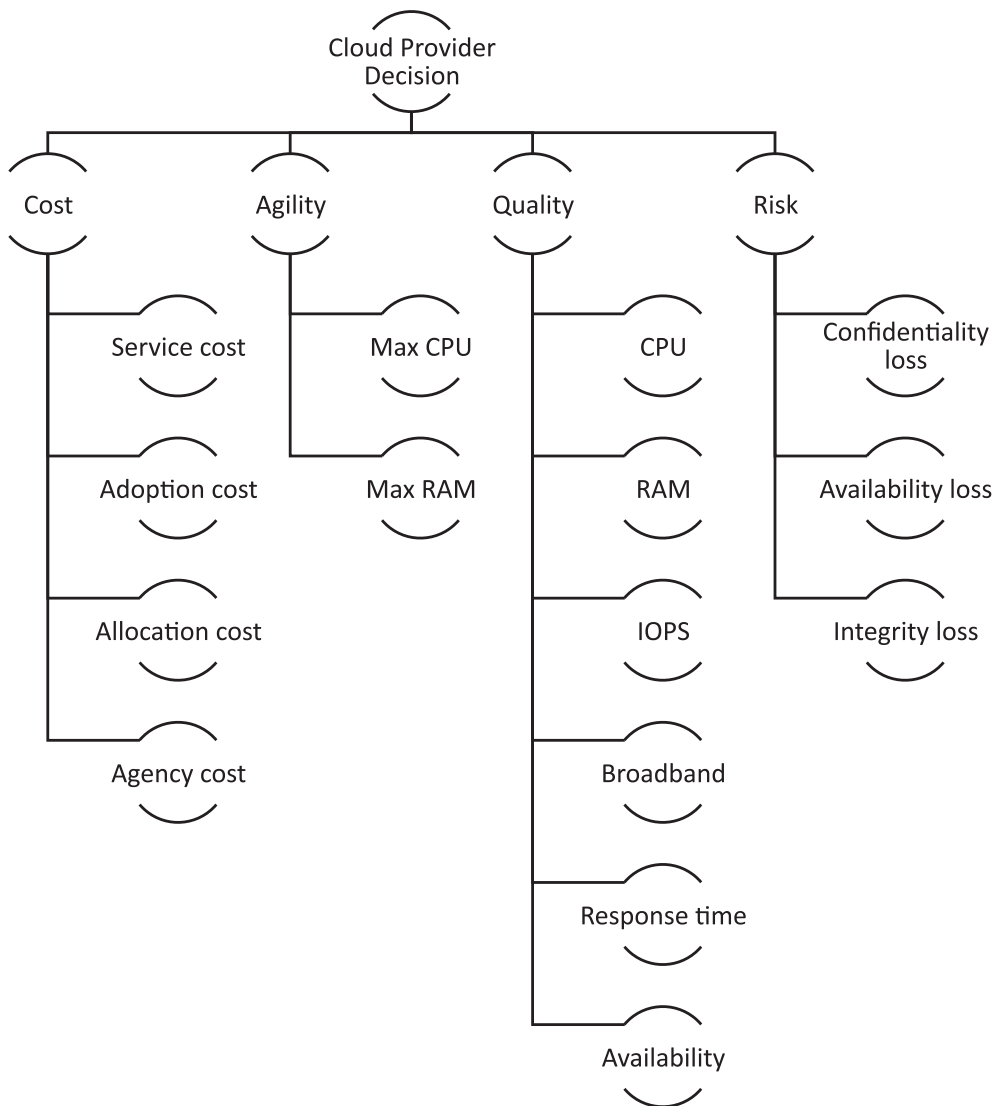


Figure 2. Hierarchy process

mance management. Allocation costs are costs associated with multi-sourcing and provider management. Adoption costs include integration and interoperability costs.

Agility - Agility refers to how quickly new capabilities are integrated into an existing IT system as needed by an organization, and it is measured as a rate-of-change metric. One of the most significant advantages of cloud computing relates to its improvement of operation process agility levels. When considering agility levels, organizations wish to determine whether a service is elastic. Under this category, two sub-criteria—max CPU and max RAM—are considered when measuring the agility of different cloud services.

Quality - One main concern for enterprises that are considering adopting cloud computing relates to potential bottlenecks that can arise from the limitations of their surroundings, e.g., computing resources housed in a

cloud provider's data center-processing facilities, memory, virtual machines per physical server, storage architecture, and network bandwidth. In our model, CPU, RAM, IOPS, broadband, availability, and response time are the 6 factors used to measure the quality of cloud services. The response time of an operation pertains to the point at which a client begins the operation to the point at which the last byte reaches the client. Availability refers to period during which a system is functioning and is often described as a mission capable rate.

Risk - Risk is defined as a broad set of policies and technologies deployed to protect data, applications and associated cloud computing infrastructures. It is recognized as one of the most significant barriers to broader cloud adoption. Risks are structured in support of three common security objectives: integrity, confidentiality and availability. A number of security con-

Criteria	Sub-Criteria	Requirement/Characteristic
Cost	Service cost Allocation cost Adoption cost Agency cost	Pricing (pay-per-use), licensing costs Multisourcing, Provider management Integration costs, interoperability Monitoring costs
Agility	Max CPU Max RAM	Max CPU per instance Max RAM per instance
Quality	CPU RAM IOPS Broadband Availability Response time	Events per seconds RAM writing speed 4k random write I/O speed 1M sequential write latency Mission capable rate Time from instance begins to byte reaches
Risk	Confidentiality loss Availability loss Integrity loss	Data protection measures Interruption of data availability Undesired data manipulation

Table 2. Requirements for a formal decision model

cerns are associated with cloud-computing services (e.g., understanding who owns your data and ensuring that the selected cloud provider offers strong security measures to protect your confidential information).

3.3. Calculating priority vectors

The relative importance of each criterion is determined through a pairwise comparison of contributions of each criterion to the hierarchy. AHP multiple pairwise comparisons are based on a scale of nine levels.

$C = \{i=1, 2, \dots, n\}$ is the set of criteria. An $(n \times n)$ evaluation matrix A can be obtained from the results of a pairwise comparison of n criteria, wherein every element a_{ij} is the quotient of criteria weights

$$A = (a_{ij}), (i, j=1, 2, \dots, n) \quad (1)$$

The right eigenvector W corresponding to the largest eigenvector ($\lambda_{\max}$) refers to relative priorities

$$AW = \lambda_{\max} W \quad (2)$$

When pairwise comparisons are completely consistent, matrix A is ranked 1, and $\lambda_{\max} = n$. In such cases, we can normalize any row or column of matrix A to obtain all weights.

3.4. Evaluating logical consistency

A consistency measure of the given pairwise comparison is needed. Consistency is determined as the relation between entries of matrix A . The consistency index (CI) is defined as

$$CI = (\lambda_{\max} - n) / (n - 1) \quad (3)$$

From the final consistency ratio (CR), we can determine whether the evaluations are sufficiently consistent. The CR is calculated as the quotient of the consistency index (CI) and random consistency index (RI).

We can evaluate the consistency of decision makers and of an entire hier-

Importance Intensity	Description
1	Equal importance of both elements
3	Weak importance of one element over another
5	Strong importance of one element over another
7	Demonstrated importance of one element over another
9	Absolute importance of one element over another
2,4,6,8	Intermediate values between two adjacent judgments

Table 3. Scale of relative importance

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 4. Random consistency index

archy through consistency measurements. A value of 0.1 denotes the upper limit that we can accept for CR. When the final consistency value exceeds 0.1, the evaluation procedure must be repeated to improve consistency levels.

$$CR = CI / RI \quad (4)$$

After determining the normalized priority weight of each AHP hierarchy criterion, it is necessary to identify a means of solving cloud-provider selection problems (Tam and Tummala, 2001; Saaty, 1990).

3.5. Fuzzy logic

Fuzzy decision theory is employed to resolve human decision-making problem uncertainty. Let $P=\{p_j | j=1, 2, \dots, m\}$ be the set of alternatives and let $W=(\omega_1, \omega_2, L, \omega_m)^T$ be the set of weights of criterion C . $S_{ij} = f(c_i, p_j)$ is a characteristic index value of, c_i , $i=1, 2, \dots$, and n corresponds to the n criterion. In turn, we obtain an $m \times n$ characteristic index matrix.

$$S = \begin{pmatrix} s_{11} & s_{12} & L & s_{1n} \\ s_{21} & s_{22} & L & s_{2n} \\ L & L & L & L \\ s_{m1} & s_{m2} & L & s_{mn} \end{pmatrix} \quad (5)$$

We assume that all membership functions are linear and are divided into two types:

a. The larger value is better

$$r_{ij} = \begin{cases} 1 & s_{ij} > s_{ip} \\ (s_{ij} - s_{if}) / (s_{ip} - s_{if}) & s_{if} \leq s_{ij} \leq s_{ip} \\ 0 & s_{ij} < s_{if} \end{cases} \quad (6)$$

b. The smaller value is better

$$r_{ij} = \begin{cases} 0 & s_{ij} > s_{ip} \\ (s_{ip} - s_{ij}) / (s_{ip} - s_{if}) & s_{if} \leq s_{ij} \leq s_{ip} \\ 1 & s_{ij} < s_{if} \end{cases} \quad (7)$$

r_{ij} is the membership function of p_j , $j=1, 2, \dots, m$, which corresponds to c_i , $i=1, 2, \dots, n$. s_{if} and s_{ip} are the lower and upper limits, respectively. If there is no upper limit, $s_{ip} = \max_{j \in (1, 2, L, n)} s_{ij}$; if there is no lower limit, $s_{if} = \min_{j \in (1, 2, L, n)} s_{ij}$.

From functions (6) and (7), we can transform the characteristic index matrix (5) into a membership degree matrix:

$$R = \begin{pmatrix} r_{11} & r_{12} & L & r_{1n} \\ r_{21} & r_{22} & L & r_{2n} \\ L & L & L & L \\ r_{m1} & r_{m2} & L & r_{mn} \end{pmatrix} \quad (8)$$

From the maximum membership degree principle, we can obtain the following ideal option:

$$G = (r_{11} \vee r_{21} \vee L \vee r_{m1}, K, r_{1n} \vee r_{2n} \vee L \vee r_{mn})^T = (g_1, g^2, L, g_n)^T \quad (9)$$

$\vee$ is a max operation. The fuzzy clingy degree is

$$N(p_j, G) = 1 - D_w(p_j, G) \quad j=1, 2, \dots, m \quad (10)$$

Where $D_w(p_j, G)$ is the weighted distance. In turn,

$$N(p_j, G) = 1 - \sum_{i=1}^n w_i (g_i - r_{ij}) \quad j=1, 2, \dots, m \quad (11)$$

The alternative corresponding to the highest weighted clingy degree is the selected ideal option. The chosen alternative has the shortest possible distance from the ideal option, which is the basic principle of this method.

Using method, in the presence of different criteria, rankings can be performed by comparing the measure of closeness to the ideal option.

4. NUMERICAL EXAMPLE EVALUATION

In this section, we present our simulation-based evaluation of the fuzzy AHP approach and describe its benefits to end users. Through this evaluation, we compare cloud providers (i.e., Amazon EC2, Windows Azure, and Numergy), which are domestic and international providers for France's cloud-service market. Criteria and sub-criteria of the proposed decision-making model are introduced and identified based on cloud provider

characteristics and we assume that they are independent.

To validate our decision model, we use a large French enterprise as a case and design a questionnaire to collect data for determining the importance of each criterion and sub-criterion instead of calculating the average of various experts' options. We want only to check whether our designed model works well, not to give an official ranking of cloud services. We believe that the ranking of cloud services will vary based on various user requirements. An IT executive was interviewed, and decisions related to each level were discussed using the nine-point scale shown in Table 6. General information about the interviewer is shown in Table 5.

Question	Interviewer
Job position	CXO
Industry sector	Sales and service
Personal experience in the cloud	> 3 years
The size of enterprise	More than 250 employees
Stage of cloud-computing adoption	Starting to experiment with the cloud
Time involved in the cloud	> 3 years

Table 5. Interview record

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria
Cost	o	o	o	x	o	o	o	o	o	o	o	o	o	o	o	o	o	Quality
Cost	o	o	x	o	o	o	o	o	o	o	o	o	o	o	o	o	o	Risk
Cost	o	o	o	o	o	o	o	o	x	o	o	o	o	o	o	o	o	Agility
Quality	o	o	o	o	o	o	x	o	o	o	o	o	o	o	o	o	o	Risk
Quality	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	x	o	Agility
Risk	o	o	o	o	o	o	o	o	o	o	o	o	x	o	o	o	o	Agility

Table 6. Pair-wise comparison

4.1. Data

Compared to previous qualitative studies on cloud-provider selection, our paper focuses on the CloudScreener (payment) and Cedexis (free) databases. This paper presents the first academic study that uses a database to rank cloud services; this is one of the most important contributions of our study. Table 7 shows the sources of data on each criterion selected through the literature review.

$$A = \begin{pmatrix} 1 & 6 & 1 & 7 \\ 1/6 & 1 & 1/8 & 3 \\ 1 & 8 & 1 & 5 \\ 1/7 & 1/3 & 1/5 & 1 \end{pmatrix}$$

After generating a comparison matrix, we compute the priority vector, which is the normalized eigenvector of the matrix. Four eigenvectors are concatenated into 4 columns in matrix V (voir formule ci-dessous):

4.2. Weight calculation

Table 6 presents comparison matrix A :

$$V = \begin{pmatrix} 0.6833 & 0.8747 & 0.3110 - 0.0338i & 0.3110 + 0.0338i \\ 0.1455 & -0.0420 & -0.1258 + 0.1850i & -0.1258 - 0.1850i \\ 0.7099 & -0.4826 & 0.9140 & 0.9140 \\ 0.0892 & -0.0150 & -0.0684 - 0.1094i & -0.0684 + 0.1094i \end{pmatrix}$$

$$\lambda = \begin{pmatrix} 4.2306 & 0 & 0 & 0 \\ 0 & 0.0398 & 0 & 0 \\ 0 & 0 & -0.1352 + 0.9839i & 0 \\ 0 & 0 & 0 & -0.1352 - 0.9839i \end{pmatrix}$$

Criteria	Data source (March, 2015)
Service cost	CloudScreener
CPU	CloudScreener
RAM	CloudScreener
IOPs	CloudScreener
Broadband	CloudScreener
Risk	CloudScreener
Max CPU	CloudScreener
Max RAM	CloudScreener
Response time	Cedexis
Availability	Cedexis

Table 7. Database

The largest eigenvalue, $\lambda_{\max} = 4.2306$, is referred to as the principal eigenvalue and corresponds to the highest eigenvector.

$$V^* = \begin{pmatrix} 0.6833 \\ 0.1455 \\ 0.7099 \\ 0.0892 \end{pmatrix}$$

The normalized principal eigenvector is

$$V^{**} = \begin{pmatrix} 0.42 \\ 0.09 \\ 0.43 \\ 0.06 \end{pmatrix}$$

In turn, we obtain the consistency index ($n=4$).

$$CI = \frac{\lambda_{\max} - n}{n - 1} = \frac{4.2306 - 4}{4 - 1} = 0.077$$

Table 4 shows that for $n=4$, the random consistency index is denoted as $RI=0.9$.

$$CR = \frac{CI}{RI} = \frac{0.077}{0.9} = 0.085 < 10\%$$

Therefore, our subjective evaluation of this criteria preference is consistent, and weights of the main criteria are $(0.42, 0.09, 0.43, 0.06)^T$. Cloud provider selection is thus based on specific customer requirements, and these requirements are changeable according to different uses of cloud services. Decision parameters are prioritized and weighted and user requirements are assigned through this procedure.

4.3. Cloud service ranking

Each cloud provider offers computing capabilities to different regions and computer systems. We choose France as the assessment site, Windows as the evaluation system, and the medium instance as an example to evaluate our decision model.

$$Y = x_0 + 0.42x_1 + 0.09x_2 + 0.43x_3 + 0.06x_4 + u \quad (12)$$

Criteria	Sub-Criteria	User requirement
Cost (0.42)		$\leq 0.4\$/h$
Quality (0.09)	Response time (0.20)	$\leq 300ms$
	Availability (0.20)	$\geq 99.5\%$
	CPU(0.15)	$\geq 60events/s$
	RAM(0.15)	$\geq 1000Mo/s$
Agility (0.43)	IOPS(0.15)	≥ 2000
	Broadband(0.15)	$\geq 100000Ko/s$
	Max vCPU (0.7)	≥ 16
Risk (0.06)	Max RAM (0.3)	$\geq 100GB$
		≥ 8

Table 8. Simulation setting-design of the simulation study

Provider	Medium Instance	Large Instance	Extra-large Instance
AWS	m3.medium	M3.large	Extra large
Cloudwatt	n1.cw.standard-1	n1.cw.standard-2	n1.cw.standard-4
Google	n1.standard-1	n1.standard-2	n1-standard-4
Ikoula	m1.medium	Large	Extra
Windows Azure	standard A2	A3	A4
Numergy	small+	L+	XL+
Rackspace	4GB	8GB	15GB
Softlayer	Instance "Medium"	Instance "Large"	Instance "Extra"

Table 9. Types of instances

First, we determine the quality priority vector for the suppliers using fuzzy logic. For the CPU, RAM, IOPS, broadband and availability sub-criteria, we use "the larger value is better" membership function; however, for the factor response time, we use "the smaller value is better" membership function. In a similar way, we can obtain the pri-

ority vectors for all remaining criteria: cost, agility and risk. Then, we aggregate all criteria to determine the relative service rankings of cloud providers using the fuzzy clingy degree N . Because of legal concerns, we anonymize the providers' names and refer to them as A to H. For instance, A.1 is one of the data center locations.

Ranking	Provider	Composite Index
1	A.8	0.638455
2	A.4	0.619122
3	A.6	0,616346
4	A.5	0.536647
5	A.7	0,52856
6	E.1	0.518421
7	A.9	0,516338
8	E.2	0.506845
9	B	0,495442
10	A.1	0,45991

Table 10. Numerical results-Composite Index

Ranking	Provider	Quality/cost Index
1	E.1	3.49679
2	E.2	2.853652
3	B	2.580538
4	G.1	2.570219
5	G.2	2.194801
6	G.3	2.079185
7	G.4	1.886343
8	C.1	1.830227
9	D	1.439463
10	F.4	1.391491

Table 11. Numerical results-Quality/Cost Index

The numerical results show that the composite index ($0.222495 \rightarrow 0.638455$) and the quality/cost index ($0.017677 \rightarrow 3.49679$) differ considerably. Figure 3 shows that there is no correlation between these two rankings. Provider A

performs better than other providers included in the composite index; however, B and E are at the top of the quality/cost ranking. Therefore, determining how to define decision criteria is essential when selecting appropriate cloud providers.

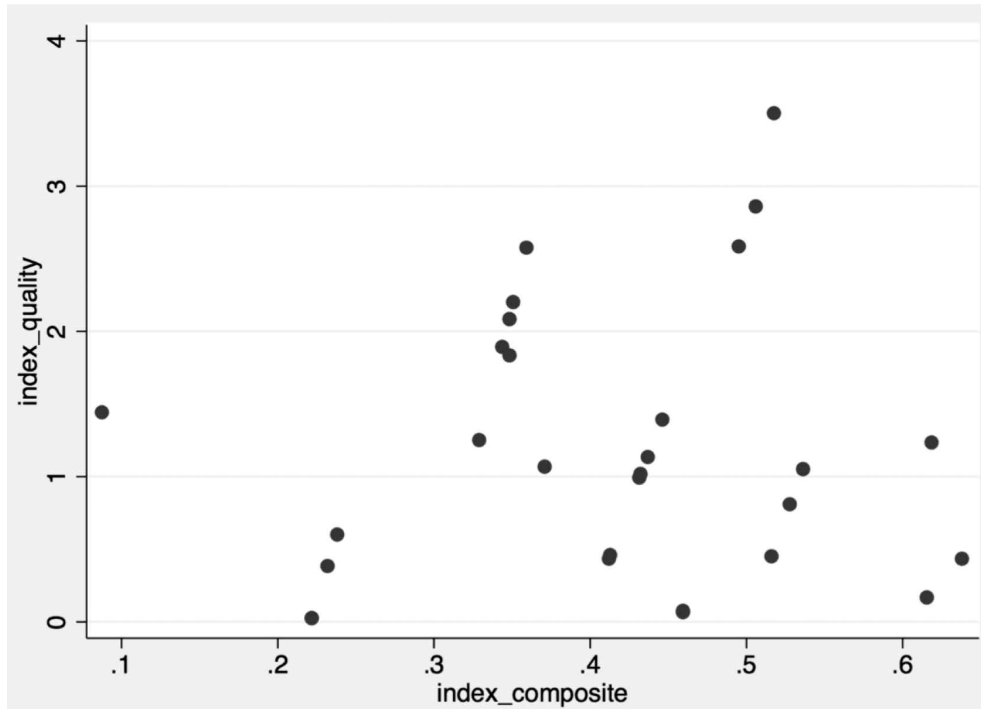


Figure 3. Results Analysis

4.4. Interdependence of criteria

Although we assume that the decision criteria are independent of one another, in reality, they are interdependent. To address this limitation, we modeled relationships between several attributes. Spearman's rank correlation coefficient was used to address the interdependence of multiple criteria. Using a monotonic function, it assesses and describes the strength of the relationship between two variables.

This approach is defined as the Pearson correlation coefficient between ranked variables. For a sample of size n , n raw scores X_i and Y_i are converted to ranks x_i , y_i , and $d_i = x_i - y_i$ is the difference between ranks, and the Spearman's rank correlation coefficient is computed from

$$\rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)} \quad (13)$$

When each of the variables is a perfect monotone function of the other, we will have a perfect correlation.

The data shown in Appendix 3 indicate no interdependence between agility and the other criteria. What is left to do is to analyze levels of interdependence between cost, risk and quality levels using Spearman's rank correlation, which shows that $\rho_{quality-cost} = 0.17$, $\rho_{quality-risk} = 0.524$, and $\rho_{cost-risk} = 0.262$. The high $\rho_{quality-risk}$ value shows that the correlation between quality and risk is very high. We must therefore account for this correlation in our decision model. Equation (12) is thus transformed into (14).

$$Y = x_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_4 x_4 + \alpha_5 x_2 x_4 + u \quad (14)$$

5. DISCUSSION

With growing attention toward long-term partnerships with better suppliers, supplier selection is increasingly viewed as an important aspect of the supply chain. Our design is based on two processes of design science, i.e., research model development and evaluation and four artifacts (hierarchy process construction, research model design, AHP method and fuzzy logic combination, and instantiation).

The simulation results show that cloud provider quality levels vary considerably. The composite and quality/cost indices show that the selection of decision criteria affects cloud service rankings. Additionally, we found a correlation between decision criteria quality and risk levels, demonstrating that it is necessary to consider correlations between multi-attributes.

Table 12 shows that this paper contributes to the IS community as prior work has not adequately addressed an important question addressed here: Is there interdependence between the selected attributes?

The contributions of this paper are outlined as follows:

- It applied the AHP method and fuzzy logic theory in identifying appropriate cloud providers.
- Simulations were based on the CloudScreener and Cedexis databases.
- It addressed interdependence between selected decision criteria.
- It proposed two comparison indexes (the composite and quality/cost indices).

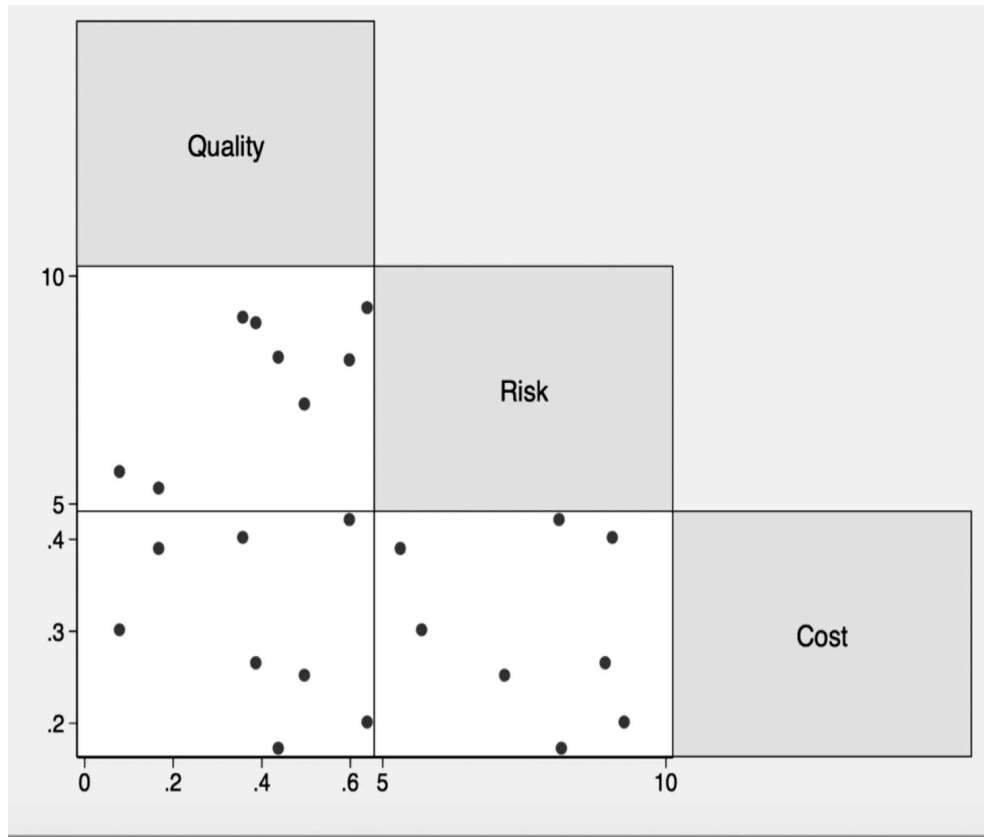


Figure 4. Correlation

Elements	Current Study	(Garg, Versteeg and Buyya, 2013)
Deployment model	IaaS+PaaS	IaaS
Decision methods	AHP and Fuzzy logic	AHP
Decision criteria	Cost, Quality, Risk, Agility	Accountability, Performance, Cost, Security, Assurance, Agility
Compared cloud providers	Amazon AWS, Cloudwatt, Google, Ikoula, Windows, Numergy, Rackspace, Softlayer	Amazon AWS, Windows, Rackspace
Data	Providers' official website and CloudScreener	Various previous studies
Interdependence	Yes	No
Results	Composite index and Quality/cost index	Composite index

Table 12. Comparison

CONCLUSION AND FUTURE RESEARCH

The model presented in this article employs a fuzzy AHP approach to compare cloud-computing services focused on IaaS and PaaS products under each selected criterion. The results of the simulation ensure the validity of the model. The research findings show that the proposed fuzzy logic theory and AHP method present a well-structured architecture and a high degree of computational power. They allow cloud customers to enhance decision-making quality levels when uncertain decision-making processes are involved.

The presented fuzzy AHP approach can be used to compare cloud providers on all service models, thus supporting teams or individuals during decision processes. We believe that our decision model is a significant step toward analyzing the process of cloud provider selection. However, there remains much to do in this paper. Like all quantitative models, our model presents some limitations that must be accounted for. In particular, our model currently focuses on cost, performance, agility and risk factors; it does not account for extensive qualitative factors that may influence cloud-computing decisions. Integrating these factors into a complete framework is a substantial challenge. Future studies must focus on these issues.

As time goes by, providers update their infrastructure and there will be more cloud providers entering the cloud market. In the future, we must update and compare more cloud providers. Developing a multi-cloud

service that combines diverse strengths of different providers is another interesting subject in this area.

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APPENDIX 1. NUMERICAL RESULTS

Provider

Provider	Composite index	Quality/cost index
A.1	0.459915	0.066566
A.2	0.459915	0.066566
A.3	0.459915	0.068728
A.4	0.619122	1.231611
A.5	0.536647	1.04547
A.6	0.616346	0.16005
A.7	0.52856	0.806481
A.8	0.638455	0.430131
A.9	0.516338	0.445315
B	0.495442	2.580538
C.1	0.348588	1.830227
C.2	0.371531	1.066826
D	0.088032	1.439463
E.1	0.518421	3.49679
E.2	0.506845	2.853652
F.1	0.432142	0.987289
F.2	0.412972	0.454796
F.3	0.437184	1.127345
F.4	0.446693	1.391491
F.5	0.43306	1.01278
F.6	0.412115	0.430987
G.1	0.359593	2.570219
G.2	0.351112	2.194801
G.3	0.3485	2.079185
G.4	0.344144	1.886343
G.5	0.329653	1.244875
H.1	0.222495	0.017677
H.2	0.222495	0.017677
H.3	0.232237	0.378461
H.4	0.238166	0.598069

APPENDIX 2. QUESTIONNAIRE

Selection of Cloud Providers

The purpose of this questionnaire is to collect data both on the given situation and on enterprise cloud service selection. The results of this questionnaire are designed to support stronger enterprise understanding of cloud computing and the creation of effective cloud-based organizations.

1. Job Position

- ☐ IT Manager
- ☐ IT Executive
- ☐ CXO (CEO, COO, CTO, CIO)
- ☐ IS Manager
- ☐ Other

2. Industry Sector

- ☐ IT
- ☐ Manufacturing
- ☐ Sales and services
- ☐ Engineering
- ☐ Public and healthcare
- ☐ Construction
- ☐ Information and communication
- ☐ Other

3. How many years of experience do you have with cloud computing?

- ☐ 0
- ☐ > 1 year
- ☐ > 3 years
- ☐ > 5 years
- ☐ > 7 years

4. What is the size of your enterprise?

- ☐ Micro-enterprise: 1-9 Employees
- ☐ Small enterprise: 10-50 Employees
- ☐ Medium enterprise: 50-250 Employees
- ☐ Large enterprise: 250+ Employees

5. How long has your enterprise been involved in cloud computing?

- ☐ 0
- ☐ > 1 year
- ☐ > 3 years
- ☐ > 5 years
- ☐ > 7 years

6. Cloud provider selection: The selection of cloud-computing suppliers is based on quantitative criteria: cost, performance, risk and agility. Quality refers to broadband access, response times, availability levels, IOPS, etc. Please rate the relative importance of each pair of items from 1 (equal importance) to 9 (high importance).

Criteria	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria
Cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Quality
Cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Risk
Cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Agility
Quality	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Risk
Quality	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Agility
Risk	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Agility

APPENDIX 3. DATA

Provider	Quality	Risk	Cost	Agility
A	0.17	5.32	0.389	1
B	0.44	8.18	0.172	0
C	0.39	8.94	0.264	0.008
D	0.60	8.14	0.42	0
H	0.64	9.28	0.2	0
E	0.36	9.08	0.4	0.740
F	0.50	7.16	0.251	0
G	0.08	5.7	0.3	0.025

Provider	Quality Q_i	Cost C_i	Rank q_i	Rank c_i	d_i	d_i^2
G	0.08	0.2	1	2	-1	1
A	0.17	0.389	2	6	-4	16
E	0.36	0.264	3	4	-1	1
C	0.39	0.251	4	3	1	1
B	0.44	0.3	5	5	0	0
F	0.50	0.4	6	7	-1	1
D	0.60	0.42	7	8	-1	1
H	0.64	0.172	8	1	7	49

Provider	Quality Q_i	Risk R_i	Rank q_i	Rank r_i	d_i	d_i^2
G	0.08	5.7	1	2	-1	1
A	0.17	5.32	2	1	1	1
E	0.36	9.08	3	7	-4	16
C	0.39	8.94	4	6	-2	4
B	0.44	8.18	5	5	0	0
F	0.50	7.16	6	3	3	9
D	0.60	8.14	7	4	3	9
H	0.64	9.28	8	8	0	0

Provider	Risk R_i	Cost C_i	Rank q_i	Rank c_i	d_i	d_i^2
A	5.32	0.389	1	6	-5	25
G	5.7	0.2	2	5	-3	9
F	7.16	0.4	3	3	0	0
D	8.14	0.42	4	8	-4	16
B	8.18	0.3	5	1	4	16
C	8.94	0.251	6	4	2	4
E	9.08	0.264	7	7	0	0
H	9.28	0.172	8	2	6	36