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# Matching Knowledge Suppliers and Demanders on a Digital Platform: A Novel Method

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**ABSTRACT** More knowledge service providers are using digital platforms to provide services, which operate under a different set of operating rules than the traditional service model. This paper presents a novel method to match knowledge suppliers and demanders on a digital platform that considers the differences between the two service models. In addition, this paper proposes an innovative approach to assess the network value to the platform provider by fuzzy multi-attribute decision making. A case study is used to show that the novel method is valid and practical. The matching method proposed in this paper extends the application of the knowledge matching method and provides a theoretical basis to improve the efficiency and profits of knowledge service platforms.

**INDEX TERMS** Digital platform, FMADM, knowledge transfer, network effects, two-sided matching.

## I. INTRODUCTION

Today, we are living in a platform economy. Apple, Amazon, Alphabet, Microsoft and Facebook, five of the 10 most valuable companies in the world today, derive much of their worth from their digital platforms. These companies facilitate interactions or transactions between parties [1]. With the development of digital technologies, such as cloud computing, Big Data, and wireless communication, digital platforms have already transformed many major industries. Many successful firms have implemented their business on a digital platform in order to fully harness what the new technology enables in terms of new interactions. There are increasingly more service providers using the platform service model [2]. The transition has overshadowed a more fundamental shift in value: the evolution to a new digital platform business model, which differs considerably from the traditional service model (e.g. the offline broker service model), with the former's operating rules being different than those for traditional firms [3].

Knowledge service is an area that is beginning to be affected by platform economics. Since resources and information are often restricted, professional knowledge services are able to ensure the successful transfer of technological knowledge and reduce the adverse effects of mismatches [4]. Increasingly more knowledge service providers are transforming to the digital platform service model, which operates under a unique set of operating rules that is from the traditional broker service model. Meanwhile the traditional knowledge service brokers make money mainly by collecting commissions. Most of the current knowledge service platforms not only provide matching services but also provide a series of complementary services, such as technology import and export services, technology evaluations, and relevant policy and legal services. These service platforms often charge very low commissions to help customers find suitable knowledge matching pairs, and then make money in the follow-up process through complementary services. The platforms either charge royalty fees from third-party complementary service providers or directly charge customers for complementary services in order to make profits. The value of the complementary services and platform can be multiplied through a positive feedback loop. As increasingly more users, service providers and other ecosystem participants adopt the same platform, these network effects make the platform and its complements increasingly more valuable (and profitable) [5]. Hence, the service model for digital platforms is not well explained by traditional matching methods. When calculating the benefits of platforms only commissions but not network effects are considered in traditional method, which is inconsistent with reality.

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Therefore, in the absence of an optimal matching theory for the knowledge service platform, the platform service model has no solid foundation for improving knowledge transfer efficiency and profits. A novel matching method is needed.

This paper's objective is to develop a matching method for a digital platform in which the network effects are considered. Based on the evaluation of the network value and the construction of the satisfaction degree, a novel matching method is proposed. In addition, the evaluation process of the network value's influencing factors has certain ambiguity and uncertainty. Fuzzy logic is an accurate method to solve imprecise and incomplete information, and so a fuzzy multi-attribute decision making model is developed in this paper to calculate the network value to a platform. Finally, a case study is conducted to illustrate the application and performance of the novel method that is proposed in this paper.

This study extends the research on matching knowledge suppliers and demanders with respect to three major dimensions. First, it is among the first attempts to develop a matching method for knowledge service providers on digital platforms, and the application of the knowledge matching method is extended. Although the matching method for knowledge service providers has been focused on by an emerging body of literature, most of them are based on the traditional broker service model, which operates under a set of different rules than the platform service model. By considering the influence of network value on the platform's revenues, the matching method proposed in this paper is more consistent with the actual situation and can better explain the matching phenomenon for the knowledge service platform that cannot be explained by the traditional matching model. Second, this paper innovatively proposes a quantitative method to calculate the network value. Most of the existing research on the evaluation of network effects uses qualitative analysis, and they are difficult to integrate into the matching model in order to select the right matching pair. Through the novel method proposed in this paper, the network value to the platform provider, which provides a reliable basis for the platform to select the appropriate matching pairs, can be quickly and easily calculated. Finally, from a realistic perspective, this research facilitates better knowledge matching on a digital platform with more robust implications for a platform strategy's sustainable development.

The rest of the paper is arranged as follows. The literature review is in Section II. Some basic concepts and theorems related to intuitionistic fuzzy numbers and digital platforms are reviewed in Section III. The matching problem for a digital platform is presented in Section IV. A novel method for matching knowledge demand and supply on a digital platform is proposed in section V. A case study, which illustrates the novel matching method's practicality and validity is presented in section VI. Section VII summarizes the conclusions.

## II. LITERATURE REVIEW

Selecting suitable knowledge matching pairs is an important service that is provided by a knowledge service platform and it is structured conveniently as a typical two-sided matching problem [6]. The two-sided matching decision problem was initially derived from the stable marriage and college admissions problem [7]. It was then extended to other fields, such as matching graduating medical residents with hospitals [8], [9], Roommate Matching [10], [11], Student-School Matching [12]–[14], and matching employees with organizations [15]–[17]. In recent years, scholars have expanded the application scope of two-sided matching theory to solve practical problems in more fields, such as the matching of Public-Private Partnership projects [18], [19], matching in organization alliances [20], [21] and resource matching in cloud-enabled vehicular networks [22], [23]. Research on matching knowledge suppliers and demanders has received increased attention in recent years. Reference [24] focused on innovation matchmaking by online intermediaries and presented three new metrics to assess the forms of the knowledge matches between demand and supply and offered recommendations to improve the online innovation intermediaries' service. Holzmann developed a matching method for innovation seekers and providers in a multisided market by considering the asymmetric partnerships between young entrepreneurial firms and incumbent large companies [25]. Reference [26] considered the attributes' expected levels from the knowledge suppliers and demanders. Reference [6] developed a matching approach considering the network collaboration effect. Reference [27] proposed an efficient and practical matching decision making method for the matching management of green building technologies' supply and demand based on intuitionistic fuzzy sets (IFS) and considering the interactions among the aspiration criteria. Liu and Li created a novel decision method for broker-assisted knowledge matching that accounted for psychological behaviors and the commissions to brokers [28].

On the other hand according to the different matching objectives, scholars have divided two-sided matching problems into different types in their studies, such as cardinality matching, weight matching and stable matching. Cardinality matching means that there is no value (weight) assigned to the matches between different subjects, and the matching is formed with the maximum number of matches as the target [29]. Weight matching refers to assigning a value (weight) to the matches between different subjects in order to form a set of matches with the maximum weight sum as the optimization objective [29]. Stable matching means that there is no weight assigned to the matches between different subjects, but the potential matches for the same subject have different importance. Therefore, the goal of matching is to make each subject try to find the other party they regard as satisfied, that is, to form two-sided matching pairs between different subjects with the goal of stable matching results [30]. Although most existing studies focus on obtaining stable matches, in some cases, each agent pays more attention to their satisfaction with the matching objects compared to stable matches [31]. According to the different matching objectives, this kind of matching problem can be considered as weight matching where weight is expressed as the satisfaction degree or benefits. According to the weight matching problem solution paradigm, the matching problem is usually transformed into a multi-objective decision problem. Many studies (such as references [6], [26], [28], [31]–[33]) start from this perspective and realize the optimal matching by building a multi-objective decision model based on the maximum matching satisfaction goal. The model that is constructed in this paper is based on these studies.

Nevertheless, most of the existing literatures related to matching knowledge suppliers and demanders are based on broker service model, which differs from the digital platform model (e.g., monetization strategies, etc.). The existing matching method in this field considers the commission but not the network value when calculating the benefits of service providers. Holding that the positive network effects are competitive advantage and the main source of value creation for digital platforms, the authors have made efforts to take network value as an important part of platform revenue. So the matching results that are inconsistent with reality are often led by this omission. Another limitation relates to existing literature is the evaluation of network value. Most of the existing research on the evaluation of network effects is qualitative analysis [34]. By which, it is difficult to calculate the network value from each matching pair to the platform provider. Existing network value measurement methods are difficult to be integrated into the matching model to select the right matching pair.

In response to the above limitations, this paper considers the difference between the traditional broker service model and the platform service model in calculating the profits of service providers and adds the network value into the calculation. For the knowledge matching on a digital platform, each agent cares more about how satisfied they are with their partners compared with stable matches. Moreover, the determination of the knowledge matching(s) is usually suggested by an intermediary. Similar to references [6], [26], and [28], the knowledge matching problem in this paper can be regarded as a weight matching problem, and the weights are determined by the satisfaction degree of each agent and the benefits of the platform provider. An improved method for knowledge matching on digital platforms is constructed. On the other hand, according to many literatures discussing the influence factors of network value, the description and evaluation of these factors need to rely on the qualitative knowledge and experience of experts to make decisions. Due to the limitation of cognition, this evaluation problem has certain ambiguity and uncertainty. Fuzzy logic is good at expressing qualitative knowledge and experience with unclear boundaries by simulating the human brain and implementing fuzzy comprehensive judgments and reasoning in order to solve regular fuzzy information problems that are difficult to solve using conventional methods [36]. So the fuzzy logic is applicable to the evaluation model of the network value for platform. This paper proposes a network value evaluation approach for the convenient calculation of the network value to platform providers by using fuzzy multi-attribute decision making.

## III. RELATED CONCEPTS

### A. INTUITIONISTIC FUZZY NUMBERS (IFNS)

Because of the fuzziness of human thinking, intuitionistic fuzzy numbers have become a very important way to represent the value of an attribute in modern decision science. In section A. the basic theories of intuitionistic fuzzy numbers are introduced. The basic theories will be used throughout this paper.

*Definition 1:* Atanassov, K. T. extended the fuzzy set to the intuitionistic fuzzy set [35]. Let X be a finite universal set, so an intuitionistic fuzzy set A is defined as:

$$A = \{< x, \mu_A(x), \nu_A(x) > |x \in X\}$$

where the degree of membership and the degree of non-membership of the element x to the set A are defined by the functions

$$\mu_A : X \to [0, 1]$$

and

$$\nu_A : X \to [0, 1]$$

respectively, with

$$0 \leq \mu_A(x) + \nu_A(x) \leq 1, \quad \forall x \in X$$

note that

$$\pi_A(x) = 1 - \mu_A(x) - \nu_A(x)$$

which is the degree of indeterminacy of x to A.

*Theorem 1:* Let $\alpha = (\mu_\alpha, \nu_\alpha), \alpha_1 = (\mu_{\alpha_1}, \nu_{\alpha_1}), \alpha_2 = (\mu_{\alpha_2}, \nu_{\alpha_2})$ be the intuitionistic fuzzy numbers, and let

$$\alpha_3 = \alpha_1 \oplus \alpha_2; \quad \alpha_4 = \alpha_1 \otimes \alpha_2;$$
$$\alpha_5 = \lambda\alpha; \quad \alpha_6 = \alpha^\lambda; \quad \lambda > 0;$$

Then

$$\alpha_i (i = 3, 4, 5, 6)$$

are intuitionistic fuzzy numbers [36].

*Theorem 2:* Let $\alpha = (\mu_\alpha, \nu_\alpha), \alpha_1 = (\mu_{\alpha_1}, \nu_{\alpha_1}), \alpha_2 = (\mu_{\alpha_2}, \nu_{\alpha_2})$ be the intuitionistic fuzzy numbers and $\lambda, \lambda_1, \lambda_2 > 0$; then

$$\begin{aligned} \alpha_1 \oplus \alpha_2 &= \alpha_2 \oplus \alpha_1; \\ \alpha_1 \otimes \alpha_2 &= \alpha_2 \otimes \alpha_1; \\ \lambda(\alpha_1 \oplus \alpha_2) &= \lambda\alpha_1 \oplus \lambda\alpha_2; \\ (\alpha_1 \otimes \alpha_2)^\lambda &= \alpha_1^\lambda \otimes \alpha_2^\lambda; \\ \lambda_1\alpha \oplus \lambda_2\alpha &= (\lambda_1 + \lambda_2)\alpha; \\ \alpha^{\lambda_1} \otimes \alpha^{\lambda_2} &= \alpha^{(\lambda_1+\lambda_2)} \text{ [36]} \end{aligned}$$

The distance measured between 2 IFNs, as defined by research [37] is used in this paper

**TABLE 1. The factors of the network value evaluation.**

| Dimension | | Factor | Description |
|---|---|---|---|
| $D_1$ Structure | $F_1$ | Number of possible connections | The possibility that the matching pair results in additional trades on the platform. |
| | $F_2$ | Centrality and Structural holes | The possibility that the matching pair bridges the structural holes in the network of the platform. |
| | $F_3$ | Network ties | The strength of the bilateral relation and the basis of cooperation for the matching pair. |
| | $F_4$ | Number of roles played by each actor | The possibility that the matching nodes of a pair assume the dual roles of knowledge supply and demand. |
| | $F_5$ | Distinctive capabilities | The possibility that a matching pair has distinctive capabilities or resources. |
| $D_2$ Conduct | $F_6$ | Opportunistic behavior | The possibility that no opportunistic behavior results from the matching pair. |
| | $F_7$ | Reputation effects | The possibility that a matching pair has a good reputation with respect to responsibility, honesty, trustworthiness, and dependability. |
| | $F_8$ | Effect of trust | The possibility that a matching pair has a deep perception of trust. |

*Definition 2:* Let $\theta_1 = (\mu_{\theta 1}, \nu_{\theta 1})$ and $\theta_2 = (\mu_{\theta 2}, \nu_{\theta 2})$ be two intuitionistic fuzzy numbers, and the normalized Hamming distance between $\theta_1$ and $\theta_2$ is defined as follows:

$$d(\theta_1, \theta_2) = \frac{1}{2}\left(|\mu_{\theta 1} - \mu_{\theta 2}| + |\nu_{\theta 1} - \nu_{\theta 2}| + |\pi_{\theta 1} - \pi_{\theta 2}|\right) \tag{1}$$

where

$$\pi_{\theta 1} = 1 - \mu_{\theta 1} - \nu_{\theta 1}$$

and

$$\pi_{\theta 2} = 1 - \mu_{\theta 2} - \nu_{\theta 2}$$

### *B. DIGITAL PLATFORMS*

A platform is defined as "a modular structure that comprises tangible and intangible resources and facilitates the interaction of actors and resources (or resource bundles)" [38]. The digital platform is used for "businesses digitally connecting members of communities to enable them to transact" [39]. Advances in digital technology have enabled this business model to scale to a global level. Moreover, it takes full advantage of the more interactions. A primary function of a digital platform is that they leverage resource liquefaction and enhance resource density and integration. The platform serves as a venue for the co-creation of value and service innovation because the resource exchanges may lead to innovative, scalable solutions. The digital platform implements a diversified monetization strategy, which is based on the positive network effects [40]. The commission revenue becomes only one, albeit less important, way to profit. In a platform business the positive network effects are competitive advantage and the main sources of value creation. When a service has more people involved, it becomes more valuable, and network effects occur. The number of relationships between 2, 5, and 12 connecters in the network is shown in Fig. 1.

## IV. STATEMENT OF THE PROBLEM

An important task of the knowledge service platform is selecting suitable matching pairs for the knowledge suppliers and demanders in order to facilitate the transactions between them. In Section III, the matching relationship between knowledge suppliers and demanders on a digital platform is described.

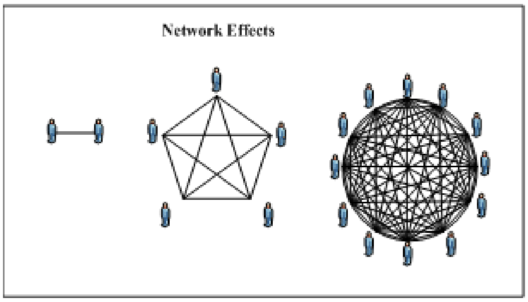

**FIGURE 1. Network effects.**

### *A. NOTATION*

$S = \{S_i \,|i = 1, 2, \ldots, m\}$ : A discrete set of $m$ technological knowledge suppliers.

$D = \left\{D_j \,|j = 1, 2, \ldots, n\right\}$ : A discrete set of $n$ technological knowledge demanders.

$E = \left\{E_g \,|g = 1, 2, \ldots, 8\right\}$ : A discrete set of attributes for evaluating the network value for a platform provider from alternative matching pairs in which the attributes are additively independent. Based on Afuah's work [41], the network value is evaluated using 8 attributes, as is shown in Table 1.

$W = \left\{w_g \,|g = 1, 2, \ldots, 8\right\}$ : The attributes' weight vector for the evaluation of the contribution of alternative matching pairs to the network value, where $w_g$is attribute $E_g$'s weight.

$A = \left[\alpha_{ij}\right]_{m\times n}$ : The satisfaction degree matrix of supplier $S_i$ with respect to demander $D_j$ for the matching decision.

$B = \left[\beta_{ij}\right]_{m\times n}$ : The satisfaction degree matrix of demander $D_j$ with respect to supplier $S_i$ for the matching decision.

$C = \left[\gamma_{ij}\right]_{m\times n}$ : The benefit matrix of the platform provider with respect to the pair of demander $D_j$ and supplier $S_i$ for the matching decision.

A decision matrix can be determined from the above notations. Selecting the suitable matching pairs for $S_i$ and $D_j$ is the task that is addressed in this paper.

### *B. DESCRIPTION OF THE TWO-SIDED MATCHING PROBLEM ON A DIGITAL PLATFORM*

For the knowledge matching on a digital platform, compared with stability matching, each agent is more concerned about his/her own satisfaction degree on his/her partner. Therefore,

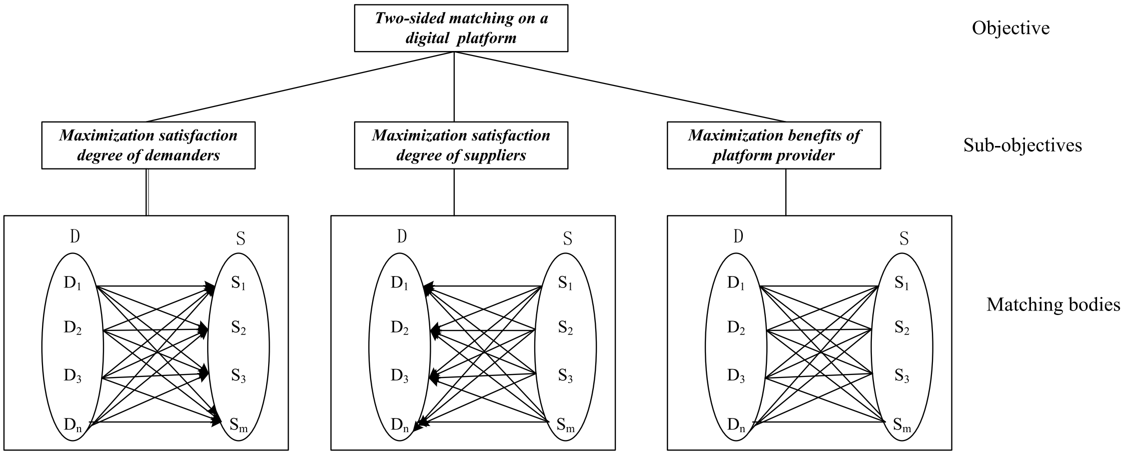

**FIGURE 2.** The structure for the two-sided matching problem on a digital platform.

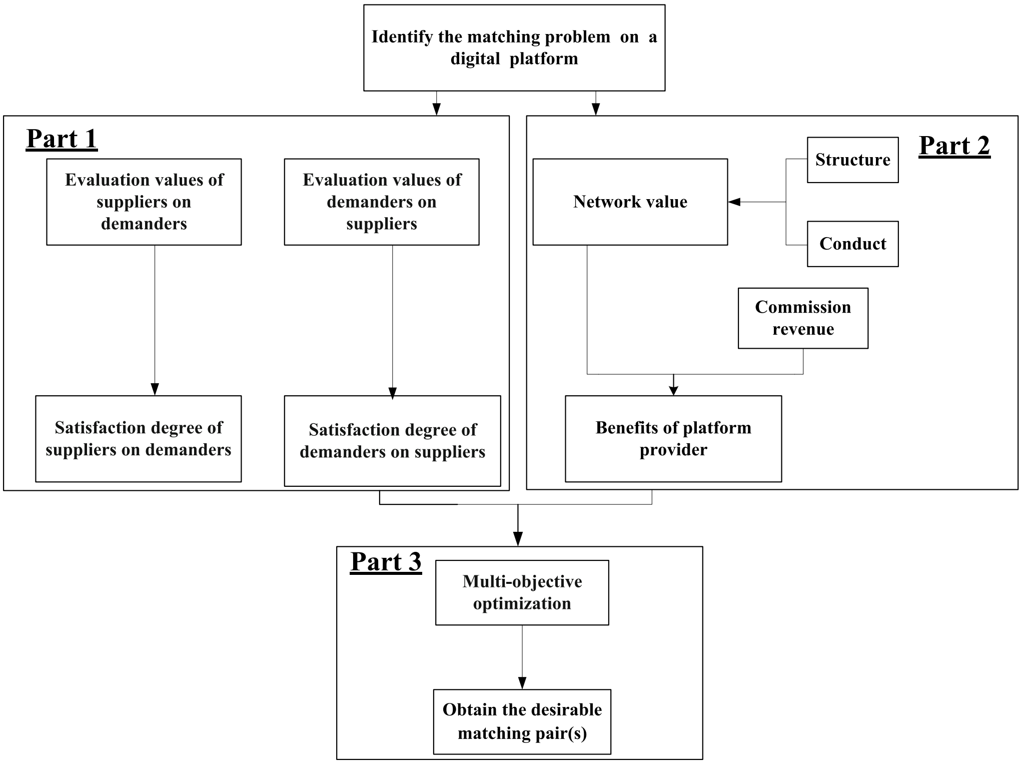

**FIGURE 3.** Composition of the matching method on a digital platform.

the determination of the knowledge match(es) is usually suggested by an intermediary. In this study, the knowledge matching problem consists of three parties: suppliers, demanders, and an independent service platform. An independent service platform is a service provider that makes the decisions regarding selecting suitable matching pairs over alternatives. $S = \{S_1, S_2, \ldots, S_m\}$ is the set of knowledge suppliers $S$, where $S_i$ denotes the *i-th* agent of side $S$, $i \in \{1, 2, \ldots, m\}$. $D = \{D_1, D_2, \ldots, D_n\}$ is the set of knowledge suppliers $D$, where $D_j$ denotes the *j-th* agent of side $D$, and $j \in (1, 2, \ldots, n)$. To solve this matching problem, three objectives must be achieved: the maximization of the satisfaction degree of $S_i$ on $D_j$. The maximization of the satisfaction degree of $D_j$ on $S_i$, and the maximization of the platform provider's benefits, which are shown in Fig. 2

## V. THE PROPOSED METHOD

There are three parts to achieve technological knowledge matching between the suppliers and demanders on a digital platform: the construction of the satisfaction degree, the evaluation of the platform provider's benefits and the multi-objective optimization (Fig. 3).

### A. A CONSTRUCTION OF THE SATISFACTION DEGREE

Let the evaluation value $a_{ij}$ be that of supplier $S_i$ on demander $D_j$, and the evaluation value $b_{ij}$ be that of demander $D_j$ on supplier side $S_i$. The evaluation value ranges from 1 to 10, where 1 indicates the lowest evaluation value and 10 indicates the highest. The satisfaction degree can be evaluated according to the evaluation value. The satisfaction degree increases as the evaluation value increases. The formulas are as follows:

$$\alpha_{ij} = \frac{a_{ij} - \min_{i} \min_{j} a_{ij}}{\max_{i} \max_{j} a_{ij} - \min_{i} \min_{j} a_{ij}}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n \tag{2}$$

$$\beta_{ij} = \frac{b_{ij} - \min_{i} \min_{j} b_{ij}}{\max_{i} \max_{j} b_{ij} - \min_{i} \min_{j} b_{ij}}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n$$
$$0 \leq \alpha_{ij} \leq 1, \quad 0 \leq \beta_{ij} \leq 1 \tag{3}$$

Then, the supplier's satisfaction degree matrix $A = [\alpha_{ij}]_{m\times n}$ and the demander's satisfaction degree matrix $B = [\beta_{ij}]_{m\times n}$ are obtained.

### B. CONSTRUCTION OF THE PLATFORM PROVIDER BENEFITS MATRIX

Unlike the traditional broker service model, the digital platform model implements a diverse monetization strategy [40]. The inherent value of a platform lies chiefly in the network effects it creates [2]. The stronger the positive network effects are, the greater the network value to the network provider is. Therefore, the benefits of the platform provider should be comprehensively considered using the commission revenue and network value. In the following section 1) an approach for the network value evaluation is described, and how to construct the benefits matrix of the platform provider is explained in the following section 2).

#### 1) EVALUATION OF THE NETWORK VALUE TO THE PLATFORM

As for the phenomenon of network effects, many studies focused primarily on the role of network size, and were largely grounded in neoclassical economics. An emerging body of work, however, suggests that many additional factors affect the network effects, such as a network's structural and conduct characteristics [41], [42]; the costs of users "multihoming" [43]; the focal product [44]; and the strength of the ties of the users in the network [45]. An influential article published in Strategic Management Journal argues that the network value is influenced by 8 factors from 2 dimensions [41]. The choice of different matching pairs impacts these factors and further affects the network effects strength of the platform. From this, the network value to the platform will also vary with the selection of different matching pairs. For example, if the matched pair has a good reputation, the reputation of the network will be improved and stronger network effects will be generated. In contrast, if users with poor historical transaction records are selected as the matched pair, it will increase the probability of opportunistic behavior on the network, thus reducing the intensity of the network effects. Another example is that if a demander with strong capital strength can be successfully matched through the platform, then it will be more willing to invest in related technologies, and more links will be brought to the platform network. Based on Afuah's work [41], the network value of each matching pair to the platform provider are evaluated from the following perspectives: a) the feasibility of the transactions, b) the members' centrality, c) the ties and structural holes in the network, d) the number of roles each network member could play, e) the opportunistic practice level, f) the network member's reputation, and g) the perception of customer network trust.

Table 1 describes the two-dimensional influential factors for evaluating the network value. There are many indicators that are involved in the evaluation of the network value, which are difficult to describe using accurate values. Thus, the technical managers from the knowledge service platform were invited to assign values to these metrics using intuitive fuzzy numbers.

Next, the network value to the platform provider is evaluated. Mcintyre noted that a promising avenue of research in the network effects is the development of survey-based measures [29]. Therefore the expert opinion method was selected to assign values to the evaluation indexes in Table 1. Because of the ambiguity of these indicators, intuitionistic fuzzy numbers were used to assign values.

Let $P = \{P_f \,|f = 1, 2, \ldots, t\}$ be a discrete set of alternative matching pairs; $E = \{E_g \,|g = 1, 2, \ldots, 8\}$ is the set of attributes; and $w_g$ is the attributes' weight vector, where $w_g \geq 0$, $g = 1, 2, \ldots, 8$, and $\sum_{g=1}^{8} w_g = 1$. Let $R = [\theta_{fg}]_{t\times s}$, where each $\theta_{fg}$ denotes the attribute value provided by the platform for the *fth* alternative $P_f$ with respect to the *gth* attribute $E_g$. Then the fuzzy matrix $R = [\theta_{fg}]_{t\times s}$ is obtained. For each alternative $P_f$, let the attribute values $\theta_{fg} = (\mu_{fg}, \nu_{fg}), (f = 1, 2, \ldots t, g = 1, 2, \ldots 8)$, be the attribute values that take the IFNs. Define the hybrid fuzzy ideal solution and the hybrid negative ideal solution as $\theta^+ = (\theta_1^+, \theta_2^+, \ldots, \theta_t^+)$ and $\theta^- = (\theta_1^-, \theta_2^-, \ldots, \theta_t^-)$, respectively. Calculate the distance between the fuzzy ideal solution (FIS) and the alternative, and the distance between the fuzzy negative ideal solution (FNIS) and the alternative using (1) as follows:

$$d_f^+ = d(\theta_f, \theta^+) = \sum_{g=1}^{8} w_g d(\theta_{fg}, \theta_g^+), \quad f = 1, 2, \ldots, t, \tag{4}$$

$$d_f^- = d(\theta_f, \theta^-) = \sum_{g=1}^{8} w_g d(\theta_{fg}, \theta_g^-), \quad f = 1, 2, \ldots, t. \tag{5}$$

When the attribute values assume intuitionistic fuzzy numbers, then

$$d(\theta_{fg}, \theta_g^+) = \frac{1}{2}(|\mu_{fg} - 1| + |\nu_{fg}| + |1 - \mu_{fg} - \nu_{fg}|),$$

$$f = 1, 2, \ldots, t; \quad g = 1, 2, \ldots, 8 \tag{6}$$

$$d(\theta_{fg}, \theta_g^-) = \frac{1}{2}(|\mu_{fg}| + |\nu_{fg} - 1| + |1 - \mu_{fg} - \nu_{fg}|), \quad f = 1, 2, \ldots t; \quad g = 1, 2, \ldots, 8 \tag{7}$$

The further the evaluation information of the matching pair from the negative ideal point, the greater the relative network value $\tilde{c}_i$ is, and the stronger the network effects are.

The network value of the alternative to the platform provider is expressed as follows:

$$\tilde{c}_f = \frac{d_f^-}{d_f^- + d_f^+}, \quad f = 1, 2, \ldots, t. \tag{8}$$

Thus, the following propositions from the analysis in this section can be obtained:

*Proposition 1:* The more likely it is that a match has good behavior (high trustworthiness and low opportunism), the more network value it brings to the platform and the stronger the network effects it creates.

*Proposition 2:* The more likely a match is to optimize the user network structure (more links and higher network strength), the more network value it brings to the platform and the stronger the network effects it creates.

### 2) CALCULATION OF THE PLATFORM PROVIDER BENEFITS MATRIX

As analyzed earlier, the benefits of the knowledge service platform should comprehensively consider the commission revenue and the network value. The purpose of establishing a benefits matrix in this paper is to compare the differences of the benefits of platform provider with respect to different matching pairs. Therefore, the concept of the relative value is used to establish the benefits of the platform provider. Then the network value to the platform provider can be calculated using Formulas (4)–(8). Using the following equations a uniform dimensional treatment is given to the expected commission revenue from alternative pairs:

$$c'_f = \frac{co_f - \min\limits_f co_f}{\max\limits_f co_f - \min\limits_f co_f}, \quad f = 1, 2, \ldots, t \tag{9}$$

where $co_f$ is the commission paid to the platform from each alternative matching pair $P_f$ when they are matched successfully. Then the decision matrix of the benefits of the platform provider can be obtained as follows:

$$C = [\gamma_{ij}]_{m\times n} = [c_f]_{m\times n} = \left[y_1\tilde{c}_f + y_2 c'_f\right]_t, \quad m \times n = t \tag{10}$$

Here, $y_1, y_2$ are the weights for $\tilde{c}_f, c'_f$, which reflect their importance in real decision making.

## *C. AN OPTIMIZATION MODEL OF MULTI-OBJECTIVE FOR THE MATCHING PROBLEM*

The two-sided matching process is described in this section. The knowledge suppliers and demanders submit the initial evaluation information of both parties to the platform. Then, the platform matches the knowledge suppliers with demanders to select suitable matching pairs. To maintain the healthy and sustainable development of a digital platform, three objectives must be achieved in this matching process: the maximization of the supplier's satisfaction degree, the maximization of the demander's satisfaction degree, and the maximization of the benefits of the platform provider. Therefore, the multiple-objective optimization model can be constructed using matrices A, B (given in Section V.A), and C (given in Section V.B), as follows:

$$\text{Maximize } Z_S = \sum_{i=1}^{m}\sum_{j=1}^{n} \alpha_{ij} x_{ij} \tag{11a}$$

$$\text{Maximize } Z_D = \sum_{i=1}^{m}\sum_{j=1}^{n} \beta_{ij} x_{ij} \tag{11b}$$

$$\text{Maximize } Z_P = \sum_{i=1}^{m}\sum_{j=1}^{n} \gamma_{ij} x_{ij} \tag{11c}$$

$$s.t. \ \sum_{j=1}^{n} x_{ij} \le 1, \quad i = 1, 2, \ldots, m \tag{11d}$$

$$\sum_{i=1}^{m} x_{ij} \le k, \quad j = 1, 2, \ldots, n \tag{11e}$$

$$x_{ij} = \{0, 1\}, \quad i = 1, 2, \ldots, m; \ j = 1, 2, \ldots, n \tag{11f}$$

In the above model, $x_{ij}$ is set as a binary variable. $x_{ij} = 1$ means that $S_i$ and $D_j$ are matched, and $x_{ij} = 0$ means that $S_i$ and $D_j$ are not matched.

Here, the objective function (11a) presents the maximization of supplier's satisfaction degree. The objective function (11b) presents the maximization of demander's satisfaction degree. The objective function (11c) represents the maximization of the benefits of the platform provider. The constraint (11d) shows that each supplier $S_i$ could be matched with 1 demander at most and reflects the practical constraints on the knowledge transfer. The constraint of the number of knowledge transfers that demander $D_j$ could accept is established by (11e). Equation (11f) reflects the decision variable constraints.

To simplify the solution of the multi-objective optimization model, the linear weighting method is used to transform the multi-objective model (11) into a single target model. Let $\lambda_1, \lambda_2, \lambda_3$ be the weights for $Z_S$, $Z_D$, and $Z_P$, respectively.

$$\text{Maximize } Z = \lambda_1 \sum_{i=1}^{m}\sum_{j=1}^{n} \alpha_{ij} x_{ij} + \lambda_2 \sum_{i=1}^{m}\sum_{j=1}^{n} \beta_{ij} x_{ij} + \lambda_3 \sum_{i=1}^{m}\sum_{j=1}^{n} \gamma_{ij} x_{ij} = \sum_{i=1}^{m}\sum_{j=1}^{n} \phi_{ij} x_{ij} \tag{12a}$$

$$s.t. \ \sum_{j=1}^{n} x_{ij} \le 1, \quad i = 1, 2, \ldots, m \tag{12b}$$

$$\sum_{i=1}^{m} x_{ij} \le k, \quad j = 1, 2, \ldots, n \tag{12c}$$

$$x_{ij} = \{0, 1\}, \quad i = 1, 2, \ldots, m; \; j = 1, 2, \ldots, n \qquad (12d)$$

$$\lambda_1 + \lambda_2 + \lambda_3 = 1$$

$$\lambda_1 \geq 0, \quad \lambda_2 \geq 0, \quad \lambda_3 \geq 0 \qquad (12e)$$

Thus, the multi-objective optimization model (11) are converted into a single objective $0-1$ integer linear programming model (12). The weights $\lambda_1, \lambda_2, \lambda_3$ reflect the importance of each objective in the actual decision making, and they vary between 0 and 1. They are usually obtained using the expert opinion method according to the actual situation. For such a model, an optimal matching solution can be obtained using software packages such as Lingo 9.0.

The proposed method for solving this matching problem has six steps in which the network effects of the platform are considered.

*Step 1:* The satisfaction matrices A and B are determined according to the suppliers' and demanders' evaluations with respect to the other party by (2) and (3), respectively.

*Step 2:* Determine the multi-attribute values in order to evaluate the network value to the platform provider from each alternative matching pair.

*Step 3:* Based on the commission revenue and network value, construct the benefits matrix of the platform provider using (10).

*Step 4:* The multiple-objective optimization model (Equations 11a–f) is established based on the satisfaction degrees from matrices A and B and the comprehensive benefits matrix C.

*Step 5:* Transform the multiple-objective optimization model (Equations 11a–f) into a single objective optimization model (Equations 12a–e).

*Step 6:* By solving the optimization model (Equations 12a–e), the optimal matching pairs can be obtained.

## VI. ILLUSTRATIVE EXAMPLE AND DISCUSSION

### A. A CASE STUDY

The authors examined the Xi'an technology resources market (TRM) as a representative knowledge service platform that promotes the matching of technological knowledge demand and supply in Xi'an, China. Xi'an is an important science and education city that produces a large number of scientific research achievements annually. In the past, many of these fail to reach the right demanders and do not realize their economic benefits in the absence of a knowledge service platform. The mismatch has significantly affected the transformation efficiency of scientific and technological achievements. For this reason, it is urgent to be able to select suitable matching pairs for technological knowledge.

TRM, which was established in 2011, is an organization that provides knowledge services using the platform model and adopts a multimonetization strategy based on network effects. This background is consistent with the purpose of this study. To show how the proposed method introduces network effects into the knowledge matching process, TRM was selected as a representative platform. In March 2017, TRM received matching requests from five patent owners ($S_1, S_2, \ldots, S_5$) and four enterprises ($D_1, D_2, \ldots, D_4$). First, the five suppliers and four demanders assessed each other according to their own needs and the other party's information. The satisfaction degree values of both sides were obtained, as shown in Table 2, by using (2) and (3). Then the technical managers from TRM surveyed the 20 possible matching pairs and invited experts to score the 20 pairs based on the 8 indicators listed in Table 1. The scores were given using intuitionistic fuzzy numbers, as shown in Table 3. Since the 8 attributes are of equal importance [41], the equal weight vector was used to calculate the network value to the platform by using (4) (5) and (8). If the 20 possible matching pairs are successfully matched, the network value they bring to the platform is listed in Table 4. A uniform dimensional treatment was conducted to the expected commission revenue from each possible matching pair using (9). The values are listed in Table 5.

**TABLE 2.** **The satisfaction degree values of the supply and demand sides.**

| | $D_1$ | $D_2$ | $D_3$ | $D_4$ |
|---|---|---|---|---|
| $S_1$ | 0.43, 0.38 | 0.52, 0.54 | 0.29, 0.81 | 0.00, 0.69 |
| $S_2$ | 0.90, 0.46 | 0.52, 0.39 | 1.00, 0.62 | 0.33, 0.27 |
| $S_3$ | 0.57, 0.31 | 0.43, 0.35 | 0.19, 0.04 | 0.62, 0.00 |
| $S_4$ | 0.52, 1.00 | 1.00, 0.50 | 0.29, 0.46 | 0.90, 0.04 |
| $S_5$ | 0.38, 0.31 | 0.33, 0.81 | 0.00, 0.38 | 0.48, 0.35 |

The decision matrix of the benefits of the platform provider can be obtained using (10) (the elements of the matrix are shown in Table 6). Considering the development stage of the TRM platform, the weights in (10) were determined to be $y_1$ $=0.9$ and $y_2$ $=0.1$ by the experts from TRM. Then a multi-objective optimization model was constructed using (11a–f). Then the single-objective optimization model was obtained using the weighted average method. According to the expert opinions, the three weights are equivalent. To ensure the service efficiency, the platform established the constraint on demanders that the maximum number of patents that may be accepted is 2. Based on the model represented in (12a–e), the matching results (($S_1$-$D_2$), ($S_2$-$D_1$), ($S_3$-$D_1$), ($S_4$-$D_2$), and ($S_5$-$D_4$)) were obtained using a software package (LINGO 9.0).

### B. DISCUSSION

In this novel method, when calculating the benefits of the platform, the changes in the weights $y_1, y_2$ in (10) are used to indicate the importance of commission revenue and network value to a platform in the matching process respectively. Obviously, the matching result will change as $y_1$ and $y_2$ change. The results from the sensitivity analysis are presented in Table 7.

Since the values of $y_1$ and $y_2$ were changed, the 11 different cases are analyzed and the three different sets of matching results are obtained as shown in Figs 4–6.

**TABLE 3.** The assesments of the network value for 20 possible matching pairs with eight attributes.

| | $E_1$ | $E_2$ | $E_3$ | $E_4$ | $E_5$ | $E_6$ | $E_7$ | $E_8$ |
|---|---|---|---|---|---|---|---|---|
| $P_1$ | (0.92,0.02) | (0.96,0.03) | (0.92,0.08) | (0.93,0.06)) | (0.90,0.09) | (0.97,0.02) | (0.95,0.02) | (0.95,0.02) |
| $P_2$ | (0.75,0.23) | (0.89,0.03) | (0.75,0.12) | (0.87,0.08) | (0.77,0.21) | (0.68,0.12) | (0.88,0.05) | (0.76,0.08) |
| $P_3$ | (0.11,0.86) | (0.12,0.79) | (0.02,0.94) | (0.06,0.89) | (0.03,0.88) | (0.06,0.83) | (0.11,0.87) | (0.02,0.94) |
| $P_4$ | (0.82,0.17) | (0.85,0.06) | (0.79,0.11) | (0.82,0.09) | (0.87,0.12) | (0.75,0.13) | (0.69,0.11) | (0.78,0.09) |
| $P_5$ | (0.86,0.07) | (0.88,0.09) | (0.87,0.01) | (0.76,0.15) | (0.78,0.12) | (0.86,0.13) | (0.65,0.18) | (0.87,0.11) |
| $P_6$ | (0.76,0.18) | (0.78,0.12) | (0.68,0.09) | (0.76,0.20) | (0.81,0.07) | (0.79,0.11) | (0.68,0.08) | (0.79,0.18) |
| $P_7$ | (0.09,0.63) | (0.11,0.79) | (0.08,0.75) | (0.13,0.87) | (0.21,0.77) | (0.06,0.83) | (0.08,0.91) | (0.04,0.81) |
| $P_8$ | (0.76,0.21) | (0.68,0.23) | (0.79,0.18) | (0.76,0.18) | (0.76,0.09) | (0.79,0.11) | (0.80,0.13) | (0.78,0.11) |
| $P_9$ | (0.68,0.12) | (0.88,0.11) | (0.87,0.06) | (0.75,0.09) | (0.87,0.10) | (0.65,0.11) | (0.76,0.12) | (0.78,0.07) |
| $P_{10}$ | (0.56,0.22) | (0.55,0.21) | (0.69,0.18) | (0.77,0.14) | (0.67,0.09) | (0.75,0.13) | (0.76,0.12) | (0.78,0.16) |
| $P_{11}$ | (0.07,0.82) | (0.19,0.72) | (0.07,0.92) | (0.09,0.81) | (0.14,0.81) | (0.17,0.79) | (0.06,0.91) | (0.07,0.89) |
| $P_{12}$ | (0.91,0.04) | (0.78,0.08) | (0.92,0.03) | (0.89,0.03) | (0.86,0.11) | (0.82,0.11) | (0.79,0.11) | (0.90,0.08) |
| $P_{13}$ | (0.58,0.12) | (0.78,0.21) | (0.65,0.23) | (0.65,0.21) | (0.73,0.18) | (0.81,0.11) | (0.78,0.09) | (0.81,0.10) |
| $P_{14}$ | (0.43,0.21) | (0.56,0.23) | (0.67,0.21) | (0.68,0.23) | (0.54,0.31) | (0.58,0.23) | (0.66,0.19) | (0.66,0.23) |
| $P_{15}$ | (0.07,0.89) | (0.07,0.92) | (0.18,0.73) | (0.15,0.71) | (0.07,0.89) | (0.03,0.94) | (0.06,0.85) | (0.09,0.88) |
| $P_{16}$ | (0.44,0.22) | (0.77,0.16) | (0.68,0.13) | (0.75,0.14) | (0.79,0.18) | (0.80,0.18) | (0.74,0.22) | (0.71,0.18) |
| $P_{17}$ | (0.43,0.35) | (0.82,0.08) | (0.78,0.15) | (0.79,0.16) | (0.78,0.16) | (0.88,0.08) | (0.86,0.11) | (0.85,0.12) |
| $P_{18}$ | (0.31,0.56) | (0.35,0.56) | (0.24,0.63) | (0.18,0.45) | (0.54,0.41) | (0.38,0.59) | (0.40,0.58) | (0.49,0.35) |
| $P_{19}$ | (0.02,0.88) | (0.13,0.76) | (0.11,0.79) | (0.06,0.91) | (0.18.0.80) | (0.08,0.89) | (0.02,0.95) | (0.07,0.89) |
| $P_{20}$ | (0.56,0.23) | (0.79,0.13) | (0.64,0.23) | (0.72,0.27) | (0.62,0.15) | (0.62,0.15) | (0.65,0.16) | (0.63,0.24) |

**TABLE 4.** The network value of 20 possible matching pairs.

| | $D_1$ | $D_2$ | $D_3$ | $D_4$ |
|---|---|---|---|---|
| $S_1$ | 0.9388 | 0.8110 | 0.1171 | 0.6461 |
| $S_2$ | 0.7831 | 0.7814 | 0.1848 | 0.7824 |
| $S_3$ | 0.8040 | 0.7321 | 0.1574 | 0.8686 |
| $S_4$ | 0.7533 | 0.6567 | 0.1403 | 0.7396 |
| $S_5$ | 0.7895 | 0.4310 | 0.1316 | 0.6993 |

**TABLE 5.** The expected commissions of 20 possible matching pairs (The normalized value).

| | $D_1$ | $D_2$ | $D_3$ | $D_4$ |
|---|---|---|---|---|
| $S_1$ | 0.0385 | 0.0000 | 0.0256 | 0.1154 |
| $S_2$ | 0.1923 | 0.1795 | 0.3590 | 0.1410 |
| $S_3$ | 0.4359 | 0.2436 | 0.2821 | 0.1923 |
| $S_4$ | 0.6667 | 0.5256 | 0.5641 | 0.6154 |
| $S_5$ | 0.8333 | 0.8718 | 1.0000 | 0.7179 |

**TABLE 6.** The comprehensive benefits of 20 possible matching pairs to the platform provider.

| | $D_1$ | $D_2$ | $D_3$ | $D_4$ |
|---|---|---|---|---|
| $S_1$ | 0.8488 | 0.7299 | 0.1080 | 0.5930 |
| $S_2$ | 0.7240 | 0.7212 | 0.2022 | 0.7183 |
| $S_3$ | 0.7672 | 0.6833 | 0.1698 | 0.8010 |
| $S_4$ | 0.7447 | 0.6436 | 0.1827 | 0.7272 |
| $S_5$ | 0.7939 | 0.4750 | 0.2184 | 0.7012 |

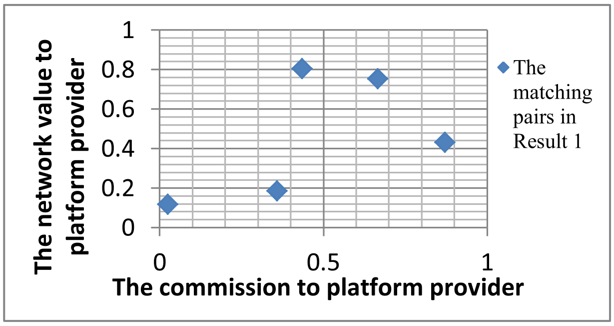

**FIGURE 4.** Matching result 1 in sensitivity analysis.

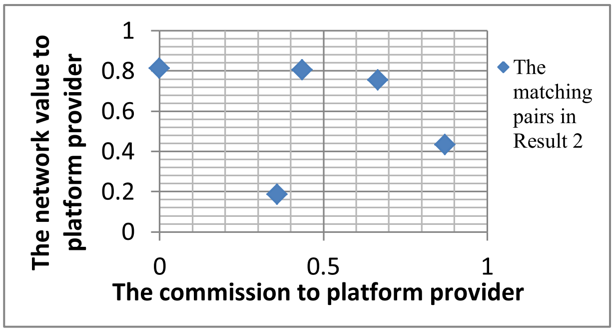

**FIGURE 5.** Matching result 2 in sensitivity analysis.

*Result 1:* When $(y_1, y_2)$ is set as (0,1), the matching results are: $x_{13} = 1, x_{23} = 1, x_{31} = 1, x_{41} = 1, x_{52} = 1$, and the others are 0. In this situation, TRM will match $S_1$-$D_3$, $S_2$-$D_3$, $S_3$-$D_1$, $S_4$-$D_1$, and $S_5$-$D_2$. The sum of the commissions that the above matching pairs will bring to the platform is 2.3590, and the sum of the network value from the above matching pairs is 2.2971. In this case, the platform is regarded as a traditional broker that does not consider network effects. This case is considered by many previous studies, such as the research of Liu *et al.* [28]

*Result 2:* When $(y_1, y_2)$ has one of the following values (0.1,0.9), (0.2,0.8), (0.3,0.7), (0.4,0.6), (0.5,0.5), (0.6,0.4),

**TABLE 7. Sensitivity analysis.**

| $y_1$ | $y_2$ | Matching results | Matching pairs recommended | Commission revenue | Network value |
|---|---|---|---|---|---|
| 0.0 | 1.0 | $x_{13}=1, x_{23}=1, x_{31}=1, x_{41}=1, x_{52}=1$ others are 0 | $S_1$-$D_3$,$S_2$-$D_3$,$S_3$-$D_1$,$S_4$-$D_1$,$S_5$-$D_2$ | 2.3590 | 2.2971 |
| 0.1 | 0.9 | $x_{12}=1, x_{23}=1, x_{31}=1, x_{41}=1, x_{52}=1$ others are 0 | $S_1$-$D_2$,$S_2$-$D_3$,$S_3$-$D_1$,$S_4$-$D_1$,$S_5$-$D_2$ | 2.3334 | 2.9190 |
| 0.2 | 0.8 | $x_{12}=1, x_{23}=1, x_{31}=1, x_{41}=1, x_{52}=1$ others are 0 | $S_1$-$D_2$,$S_2$-$D_3$,$S_3$-$D_1$,$S_4$-$D_1$,$S_5$-$D_2$ | 2.3334 | 2.9190 |
| 0.3 | 0.7 | $x_{12}=1, x_{23}=1, x_{31}=1, x_{41}=1, x_{52}=1$ others are 0 | $S_1$-$D_2$,$S_2$-$D_3$,$S_3$-$D_1$,$S_4$-$D_1$,$S_5$-$D_2$ | 2.3334 | 2.9190 |
| 0.4 | 0.6 | $x_{12}=1, x_{23}=1, x_{31}=1, x_{41}=1, x_{52}=1$ others are 0 | $S_1$-$D_2$,$S_2$-$D_3$,$S_3$-$D_1$,$S_4$-$D_1$,$S_5$-$D_2$ | 2.3334 | 2.9190 |
| 0.5 | 0.5 | $x_{12}=1, x_{23}=1, x_{31}=1, x_{41}=1, x_{52}=1$ others are 0 | $S_1$-$D_2$,$S_2$-$D_3$,$S_3$-$D_1$,$S_4$-$D_1$,$S_5$-$D_2$ | 2.3334 | 2.9190 |
| 0.6 | 0.4 | $x_{12}=1, x_{23}=1, x_{31}=1, x_{41}=1, x_{52}=1$ others are 0 | $S_1$-$D_2$,$S_2$-$D_3$,$S_3$-$D_1$,$S_4$-$D_1$,$S_5$-$D_2$ | 2.3334 | 2.9190 |
| 0.7 | 0.3 | $x_{12}=1, x_{23}=1, x_{31}=1, x_{41}=1, x_{52}=1$ others are 0 | $S_1$-$D_2$,$S_2$-$D_3$,$S_3$-$D_1$,$S_4$-$D_1$,$S_5$-$D_2$ | 2.3334 | 2.9190 |
| 0.8 | 0.2 | $x_{12}=1, x_{23}=1, x_{31}=1, x_{41}=1, x_{52}=1$ others are 0 | $S_1$-$D_2$,$S_2$-$D_3$,$S_3$-$D_1$,$S_4$-$D_1$,$S_5$-$D_2$ | 2.3334 | 2.9190 |
| 0.9 | 0.1 | $x_{12}=1, x_{21}=1, x_{31}=1, x_{42}=1, x_{54}=1$ others are 0 | $S_1$-$D_2$,$S_2$-$D_1$,$S_3$-$D_1$,$S_4$-$D_2$,$S_5$-$D_4$ | 1.8717 | 3.5659 |
| 1,0 | 0.0 | $x_{12}=1, x_{21}=1, x_{31}=1, x_{42}=1, x_{54}=1$ others are 0 | $S_1$-$D_2$,$S_2$-$D_1$,$S_3$-$D_1$,$S_4$-$D_2$,$S_5$-$D_4$ | 1.8717 | 3.5659 |

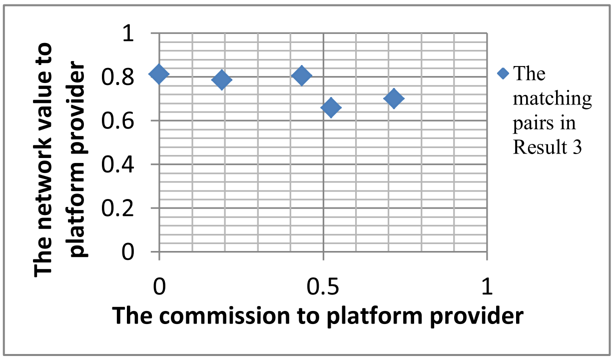

**FIGURE 6. Matching result 3 in sensitivity analysis.**

(0.7,0.3), or (0.8,0.2), the matching results are: $x_{12} = 1$, $x_{23} = 1, x_{31} = 1, x_{41} = 1, x_{52} = 1$ and the others are 0. In this situation, TRM will match $S_1$-$D_2$, $S_2$-$D_3$, $S_3$-$D_1$, $S_4$-$D_1$, and $S_5$-$D_2$ The sum of the commissions that the above matching pairs will bring to the platform is 1.8717, and the sum of the network value from the matching pairs is 3.5659. In this case, the platform provider considers both commission revenue and network value when making matching choices.

*Result 3:* When $(y_1, y_2)$ is (0.9,0.1), which is the value adopted in this case study, or $(y_1, y_2)$ is (1,0), the matching result is: $x_{12} = 1, x_{21} = 1, x_{31} = 1, x_{42} = 1, x_{54} = 1$ and the others are 0. In this situation, TRM will match $S_1$-$D_2$, $S_2$-$D_1$, $S_3$-$D_1$, $S_4$-$D_2$, and $S_5$-$D_4$ The sum of the commissions that the above matching pairs will bring to the platform is 1.8717, and the sum of the network value from the matching pairs is 3.5659. The condition that platform provider only considers the network value without considering the commission revenue when making matching choices belongs to this kind.

It can be seen from the above analysis that the matching results and platform benefits are changing as the service provider changes its service model (from the traditional broker model to the platform model). Moreover, whether the network effects are considered or not, the matching results given by the platform, the commission income and the network value of the platform are greatly different.

In the case study, an interesting phenomenon is found, which could not be explained by the traditional matching method but could be well explained by the model proposed in this paper. Under the premise that the satisfaction of both the knowledge supply and demand remains unchanged, in some cases, the platform provider is more likely to select the matching pair that pays a lower commission to the platform rather than the matching pair that pays a higher commission. The larger the ratio of $y_1$ to $y_2$ is, the more likely the platform is to choose those matching pairs with lower commissions and greater network value. For example, as the ratio of $y_1$ to $y_2$ increases, the platform is more inclined to choose the matching pairs with $D_4$, although the pairs with $D_4$ are willing to pay lower commissions. (The commission from pair $S_5$-$D_4$ is 7.6 million Yuan and that from pair $S_5$-$D_2$ is 8.8 million Yuan.) As the ratio increases, the platform is less inclined to choose the matching pairs with $D_3$, although the pairs with $D_3$ are willing to pay higher commissions. (The commission from pair $S_1$-$D_3$ is 2.2 million Yuan and that from pair $S_1$-$D_2$ is 2.1 million Yuan. The commission from $S_2$-$D_3$ is 4.8 million Yuan and that from $S_2$-$D_1$ is 3.5 million Yuan.) TRM, as a knowledge service platform, evaluates the customers based on their aggregate information and technology transaction records. We know from the survey of with TRM, the evaluation from TRM shows that $D_3$ has a poor track record, and so the technical manager thinks that matching pairs with $D_3$ would bring less network value to the platform and possibly create negative network effects; thus, the platform did not tend to select matching pairs with $D_3$. Conversely, the network value to the platform provider is greater from pairs with demander $D_4$ due to its special industry status and strong ability for technology incubation. $D_4$ is an important selection target, even though the commission revenues from pairs with $D_4$ are less than others. The final result that is obtained by this proposed matching method accurately reflects reality.

The case study verified the practicality and validity of the proposed method. Moreover, there is the fact that cannot be explained by the traditional matching method but is explained well by the novel method proposed in this paper. In addition, the sensitivity analysis can help platform providers select the required matching pairs according to the strategic objectives at different stages of platform development.

## VII. CONCLUSIONS

Selecting suitable matching knowledge supplier and demander pairs is an important knowledge service. Increasingly knowledge service providers are transforming to the digital platform service model, which operates under a unique set of operating rules that are different from the traditional broker service model. This paper combined knowledge services, the platform business model and network theories to explore the matching method for knowledge suppliers and demanders on a digital platform. A multi-objective matching approach is proposed. Furthermore, when considering the benefits of the platform, this paper innovatively proposes a network value evaluation method using the fuzzy multi-attribute decision model. Then a case study is used to demonstrate how to solve a matching problem for a digital platform. The case study verifies the practicality and validity of the proposed method.

This study has the following contributions to the current scholarly literature. First, this study extends the application of the knowledge matching method to the platform service model, which is a new influential trend that operates under a different set of rules from the tradition service model. Moreover, some matching phenomena that occur in the platform service model cannot be explained by the traditional matching method. The study represents one of the first attempts to fill this important gap by exploring the difference between the platform and the traditional broker service model, and it extends the application of the knowledge matching method.

Second, relatedly, this paper innovatively proposes a quantitative method to calculate the network value to a service platform's provider. Using this method, the network effects in different situations can be quantitatively measured and easily compared. Most of the existing research on the evaluation of network effects uses qualitative analysis, and qualitative results are difficult to integrate into the matching model to select the right matching pair. Using the novel method proposed in this paper, the network value to the platform provider, which provides a reliable basis for the platform to select the appropriate matching pairs, can be conveniently calculated.

Finally, from a realistic perspective, this research facilitates better matching between knowledge demanders and suppliers on a digital platform with more robust implications for a platform's sustainable development strategy e.g., this research can help platforms implement the subsidy strategy more effectively. In the early stage of the development of a platform, the main task is to leverage the network effects. At this time, appropriate matching strategies can be used to select matching pairs in order to leverage the network effects. In this process, the selection of matching pairs that do not use commission maximization as the standard is actually a subsidy strategy. The matching strategy proposed in this paper can help the platform to determine the subsidy objects.

The following limitations should be noted in this study. First, this paper establishes a matching method based on the goal of maximizing the satisfaction. Although many studies have established matching methods based on satisfaction maximization as the goal, their scopes of application are limited to a certain extent. The matching method constructed in this paper is applicable to some cases, in which each agent cares more about how satisfied they are with their partners compared to stable matches. Therefore, summarizing the research results and applying them to platforms should be cautious in different environments.

Moreover, the proposed model does not differentiate between the stages of platform development. In the different stages of platform development, the network value and commission revenue account for different proportions of platform benefits. In view of these limitations, future research needs to differentiate between the stages of platform development. The proposed method can be improved by adding constraints or goals in the different stages and application fields.

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## REFERENCES

[1] A. Hagiu and E. J. Altman, "Finding the platform in your product four strategies that can reveal hidden value," *Harvard Bus. Rev.*, vol. 95, no. 4, pp. 94–100, Jul./Aug. 2017.

[2] M. W. Van Alstyne, S. P. Choudary, and G. G. Parker, *Platform Revolution—How Networked Markets are Transforming the Economy and How to Make Them Work for You*. New York, NY, USA: W. W. Norton & Company, 2016.

[3] D. S. Evans and R. Schmalensee, "What platforms do differently than traditional businesses," *Harvard Bus. Rev. Digit. Articles*, vol. 2016, pp. 2–5, May 2016.

[4] I. Miles, "Knowledge intensive business services: Prospects and policies," *Foresight*, vol. 7, no. 6, pp. 39–63, 2013.

[5] M. A. Cusumano, "The platform leader's dilemma," *Commun. ACM*, vol. 54, no. 10, pp. 21–24, Oct. 2011.

[6] J. Han, B. Li, H. Liang, and K. K. Lai, "A novel two-sided matching decision method for technological knowledge supplier and demander considering the network collaboration effect," *Soft Comput.*, vol. 22, no. 16, pp. 1–13, 2018, doi: 10.1007/s00500-018-3131-z.

[7] D. Gale and L. S. Shapley, "College admissions and the stability of marriage," *Amer. Math. Monthly*, vol. 69, no. 1, pp. 9–15, 1962.

[8] A. E. Roth, "The evolution of the labor market for medical interns and residents: A case study in game theory," *J. Political Econ.*, vol. 92, no. 6, pp. 991–1016, 1984.

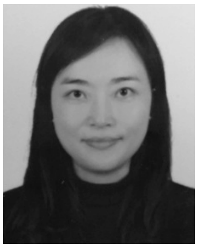
[9] A. E. Roth, "New physicians: A natural experiment in market organization," *Science*, vol. 250, no. 4987, pp. 1524–1528, 1990.

[10] D. Gusfield, "The structure of the stable roommate problem: Efficient representation and enumeration of all stable assignments," *SIAM J. Comput.*, vol. 17, no. 4, pp. 742–769, 1988.

[11] R. W. Irving, "An efficient algorithm for the 'stable roommates' problem," *J. Algorithms*, vol. 6, no. 1, pp. 577–595, 1985.

[12] A. E. Roth, "The college admissions problem is not equivalent to the marriage problem," *J. Econ. Theory*, vol. 36, no. 2, pp. 277–288, 1985.

[13] D. G. Mcvitie and L. B. Wilson, "The application of the stable marriage assignment to university admissions," *Oper. Res. Quart.*, vol. 21, no. 4, pp. 425–433, 1970.
[14] E. M. Azevedo and J. D. Leshno, "A supply and demand framework for two-sided matching markets," *J. Political Econ.*, vol. 124, no. 5, pp. 1235–1268, 2016.
[15] D. M. Cable and T. A. Judge, "Pay preferences and job search decisions: A person-organization fit perspective," *Personnel Psychol.*, vol. 47, no. 2, pp. 317–348, 1994.
[16] J. R. Edwards, "Person-job fit: A conceptual integration, literature review and methodological critique," *Int. Rev. Ind. Organizational Psychol.*, vol. 6, pp. 283–357, Jan. 1991.
[17] M. Rickley, "Estimating the determinants of executive selection in multinational companies: A two-sided matching model," *Eur. J. Int. Manage.*, vol. 12, nos. 5–6, pp. 596–623, 2018.
[18] P. Wang, J. Shen, and B. Zhang, "A new method for two-sided matching decision making of PPP projects based on intuitionistic fuzzy choquet integral," *J. Intell. Fuzzy Syst.*, vol. 31, no. 4, pp. 2221–2230, 2016.
[19] R. Liang, C. Wu, Z. Sheng, Zhaohan, and X. Wang, "Multi-criterion two-sided matching of public–private partnership infrastructure projects: Criteria and methods," *Sustainability*, vol. 10, no. 4, p. 1178, 2018, doi: 10.3390/su10041178.
[20] A. Banal-Estañol, I. Macho-Stadler, and D. Pérez-Castrillo, "Endogenous matching in university-industry collaboration: Theory and empirical evidence from the United Kingdom," *Manage. Sci.*, vol. 64, no. 4, pp. 1591–1608, 2018.
[21] D. Mindruta, M. Moeen, and R. Agarwal, "A two-sided matching approach for partner selection and assessing complementarities in partners' attributes in inter-firm alliances," *Strategic Manage. J.*, vol. 37, no. 1, pp. 206–231, 2016.
[22] X. Huang, R. Yu, J. Kang, N. Wang, S. Maharjan, and Y. Zhang, "Software defined networking with pseudonym systems for secure vehicular clouds," *IEEE Access*, vol. 4, pp. 3522–3534, 2016.
[23] R. Yu *et al.*, "Cooperative resource management in cloud-enabled vehicular networks," *IEEE Trans. Ind. Electron.*, vol. 62, no. 12, pp. 7938–7951, Dec. 2015.
[24] M. Pourmohamadi and A. Dong, "Knowledge matching in the technology outsourcing context of online innovation intermediaries," *Technol. Anal. Strategic Manage.*, vol. 26, no. 6, pp. 655–668, 2014.
[25] T. Holzmann, K. Sailer, and B. Katzy, "The matching process for innovation partnerships: A multi-sided market perspective," *Proc. IEEE Int. Technol. Manage. Conf. Int. Conf. Eng., Technol. Innov.*, The Hague, The Netherlands, Jun. 2013, pp. 1–12.
[26] X. Chen, Z. Li, Z.-P. Fan, X. Zhou, and X. Zhang, "Matching demanders and suppliers in knowledge service: A method based on fuzzy axiomatic design," *Inf. Sci.*, vols. 346–347, pp. 130–145, Feb. 2016.
[27] S. Yin and B. Li, "Matching management of supply and demand of green building technologies based on a novel matching method with intuitionistic fuzzy sets," *J. Cleaner Prod.*, vol. 201, pp. 748–763, Nov. 2018.
[28] Y. Liu, K. W. Li, Y. Liu, and K. W. Li, "A two-sided matching decision method for supply and demand of technological knowledge," *J. Knowl. Manage.*, vol. 21, no. 3, pp. 592–606, 2017.
[29] B. Bollobas, *Modern Graph Theory*. Beijing, China: Science Press, 2001.
[30] D. G. McVitie and L. B. Wilson, "The stable marriage problem," *Commun. ACM*, vol. 14, no. 7, pp. 486–490, 1971.
[31] Q. Yue and Y. Li, "Two-sided matching considering the preferences of agents and intermediary," *Comput. Model New Technol.*, vol. 18, no. 11, pp. 832–835, 2014.
[32] Z.-Z. Jiang, Z.-P. Fan, W. H. Ip, and X. Chen, "Fuzzy multi-objective modeling and optimization for one-shot multi-attribute exchanges with indivisible demand," *IEEE Trans. Fuzzy Syst.*, vol. 24, no. 3, pp. 708–723, Jun. 2016.
[33] Z.-Z. Jiang, W. H. Ip, H. C. W. Lau, and Z.-P. Fan, "Multi-objective optimization matching for one-shot multi-attribute exchanges with quantity discounts in E-brokerage," *Expert Syst. Appl.*, vol. 38, no. 4, pp. 4169–4180, 2011.
[34] D. P. Mcintyre and A. Srinivasan, "Networks, platforms, and strategy: Emerging views and next steps," *Strategic Manage. J.*, vol. 38, no. 1, pp. 141–160, 2017.
[35] K. T. Atanassov, "Intuitionistic fuzzy sets," *Fuzzy Sets Syst.*, vol. 20, pp. 87–96, Aug. 1986.
[36] Z. Xu and X. Cai, *Intuitionistic Fuzzy Information Aggregation: Theory and Applications*. Beijing, China: Science Press, 2012.
[37] Z. Xu and R. R. Yager, "Dynamic intuitionistic fuzzy multi-attribute decision making," *Int. J. Approx. Reasoning*, vol. 48, no. 1, pp. 246–262, 2008.
[38] R. F. Lusch and S. Nambisan, "Service innovation: A service-dominant logic perspective," *MIS Quart.*, vol. 39, no. 1, pp. 155–175, 2015.
[39] L. C. Reillier and B. Reillier, *Platform Strategy: How to Unlock the Power of Communities and Networks to Grow Your Business*. Evanston, IL, USA: Routledge, 2017, pp. 136–146.
[40] D. S. Evans and R. Schmalensee, *Matchmakers: The New Economics of Multisided Platforms*. Brighton, MA, USA: Harvard Business Review Press, 2016.
[41] A. Afuah, "Are network effects really all about size? the role of structure and conduct," *Strategic Manage. J.*, vol. 34, no. 3, pp. 257–273, 2013.
[42] E. Lee, J. Lee, and J. Lee, "Reconsideration of the winner-take-all hypothesis: Complex networks and local bias," *Manage. Sci.*, vol. 52, no. 12, pp. 1838–1848, 2006.
[43] A. Hagiu, "Two-sided platforms: Product variety and pricing structures," *J. Econ. Manage. Strategy*, vol. 18, no. 4, pp. 1011–1043, 2010.
[44] D. P. Mcintyre and M. Subramaniam, "Strategy in network industries: A review and research agenda," *J. Manage.*, vol. 35, no. 6, pp. 1494–1517, 2009.
[45] F. F. Suarez, "Network effects revisited: The role of strong ties in technology selection," *Acad. Manage. J.*, vol. 48, no. 4, pp. 710–720, 2005.



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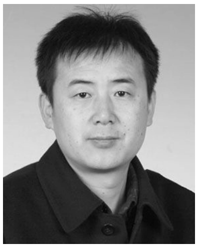

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