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Impact of Crowdsourcee's Vertical Fairness Concern on the Crowdsourcing Knowledge Sharing Behavior and Its Incentive Mechanism

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Abstract

This paper examine in detail the impact of the crowdsourcee's vertical fairness concern on the knowledge sharing incentive mechanism in crowdsourcing communities. The conditions for the establishment of the incentive mechanism is analyzed and he impact of fairness concern sensitivity on expected economic revenues of both sides as well as the crowdsourcing project performance is studied by game theory and computer simulation. The results show that the knowledge sharing incentive mechanism can only be established if the ratio between the performance improvement rate and the private cost reduction rate caused by shared knowledge is within a certain range. The degree of the optimal linear incentives, the private solution efforts, and the improvement of knowledge sharing level are positively correlated with the sensitivity of vertical fairness concern. In the non-incentive mode, the ratio between the performance conversion rate of private solution effort and the performance conversion rate of knowledge sharing effort plays an important role in moderating a crowdsourcing project's performance. We find that the number of participants is either conducive or non-conducive to the improvement of performance.

The implementation of knowledge sharing incentive can achieve a win-win situation for both the crowdsourcer and the crowdsourcee.

Keywords: vertical fairness concern; knowledge sharing; incentive mechanism; creative crowdsourcing community

Practitioners Points

- Focusing on the collaborative relationship among the crowdsourcees due to knowledge sharing, we propose the crowdsourcing project performance formula under the rules of "winner-takes-all".
- We expound the influence of the knowledge sharing incentive mechanism on the crowdsourcing project performance and analyze the influencing factors of the optimal knowledge sharing incentive coefficients.
- We discuss the impact of the crowdsourcee's vertical fairness concern on the value of the knowledge sharing incentive mechanism.

Introduction

With the development of the Internet and the prevalence of open innovation, the way for enterprises to acquire knowledge has gradually expanded from internal employers to the external public, which makes crowdsourcing popular among enterprises[1-3] (Sindlinger 2010; Bontcheva et al. 2017; Poesio et al. 2017). World-renowned companies such as P&G, Amazon and IBM have all established their own crowdsourcing communities to improve their innovation efficiency. InnoCentive, a third-party crowdsourcing innovation platform created by Eli Lilly and Company, is known because of its unique "seeker-solver" mode, which has attracted many companies to release technical problems, covering a variety of fields such as biopharmaceutical, petrochemical, aerospace, scientific research. The number of registered users has exceeded 10 million, spanning more than 70 countries and regions worldwide, arguably one of the most important channels for many large enterprises to implement open innovation[4] (Stol and Fitzgerald 2014).

The advantage of crowdsourcing innovation lies in "The crowd", gathering the wisdom of multiple participants, realizing diversified integration of knowledge, so as to solve a problem or obtain high-quality crowdsourcing solutions in a timely and effective manner. Interestingly, knowledge sharing is one of the most important motivations for the public to participate in the crowdsourcing community, which reflects one of the community's most important characteristics[5-8] (Hansen 2002; Lin et al. 2015; Yao et al. 2014; Chiu et al. 2007). At present, the most common incentive is for the crowdsourcer to offer a monetary reward which is competitively positioned. Such “crowdsourcing contest” could result in the lack of communication and interaction among the crowdsourcees and reduce the knowledge sharing under the psychological effect of fairness concern. Arguably, the risk of resource wasting is prominent, and the quality of crowdsourcing project is low.

Fairness concern can be divided into two subject areas. One is the horizontal fairness concern among the crowdsourcees, and the other is the vertical fairness concern between crowdsourcer and crowdsourcee. Interestingly, crowdsourcees with fairness concern tend to be self-interested, arguably paying more attention to the rationality of interest distribution between themselves and others under the constraints of project resources, time, and cost. Therefore, in the process of knowledge sharing, the economic benefits and distribution results will be carefully considered to maximize the individual utility of knowledge sharing [9] (Shi et al. 2015). According to relevant research, we are not amazing to see that one of the main reasons for the crowdsourcee’s reluctance to participate in competitively-driven crowdsourcing projects that could instill a feeling of unfair treatment long term [10](Hyman 2013). The value created for the enterprise is not in direct proportion to their obtained benefits, thus the realization of self-value is affected. Then, what is the mechanism of the knowledge sharing in crowdsourcing community influencing the selection effort put level? How will this affect the performance of crowdsourcing projects and the economic interests of both parties? How to design an effective incentive mechanism to enhance knowledge sharing? Will the vertical fairness concern of the crowdsourcee improve or reduce knowledge sharing behavior, and what kind of mediating effect will this have on the value of incentive mechanism? We think these problems very interesting and have strong practical significance.

Literature Review

This paper is related to the following streams of literature: crowdsourcing innovation and its incentive mechanism, knowledge sharing behavior of knowledge subjects, psychological characteristics of fairness concern.

Crowdsourcing Innovation and Its Incentive Mechanism

The concept of crowdsourcing, first proposed by Jeff Howe in Wired Magazine in 2006, indicates that crowdsourcing enables innovation which traditionally needs to be implemented by internal employees to be outsourced to a large, undefined group [11](Howe 2008). Goodman and Paolacci[12](2017), Mahmood et al.[13](2015) elaborated on crowdsourcing innovation in Data collection and outsourcing. They all attributed its development to the computer and communication technology. From the perspectives of processes and motivations, crowdsourcing innovation is divided into two types: collaborative crowdsourcing[14] (Feyisetan and Simperl 2017) and crowdsourcing contest. Crowdsourcing innovation consists of three main dimensions: crowdsourcer (or sponsor), crowdsourcee (or solver), and crowdsourcing platform. The crowdsourcer can be an individual, a public institution, a company, or even a non-profit organization[15] (Estellés 2012). The crowdsourcing platform is not necessarily built by the crowdsourcer but can be created and operated by an intermediary company, which is mainly dedicated to providing innovative solutions for enterprises [16](Bartek et al. 2017). Crowdsourcees come from all over the world, they gather together through the Internet and communicate with each other by information technology [17](Ipeirotis and Gabrilovich 2015).

How to improve the project performance (or project quality) is a main problem of crowdsourcing,which raises the enthusiasm for incentive mechanism study of which the basis is the participation motivation of the crowdsource[18] (Terwiesch and Yi 2008). Material needs such as money, job opportunities are undoubtedly important motivational factors[19] (Alsayasneh et al. 2017), the non-physical needs of knowledge acquisition and sharing[20] (Ahmad et al. 2017), propaganda and self-development[21] (Calma et al. 2018), trust[22] (Stahlbrost and Kareborn 2011) should not be neglected. Luo and Tham[23] (2012) proposed two types of incentive mechanisms respectively to maximize social utility. Wu et al.[24] (2015) set an incentive mechanism based on the internet user's historical service credibility; Zhang et al. [25](2015) established three auction models according to the number of service platforms and user bids. The above incentive mechanism is mainly aimed at the competitive relationship among the crowdsourcees in crowdsourcing innovation. On the rule of the "winner-takes-all" in crowdsourcing contest, we pay more attention to the collaborative relationship among the crowdsourcees due to knowledge sharing, especially, we explore how this collaborative relationship is deeply maintained and how it affects the quality and performance of the crowdsourcing project.

Knowledge Sharing Behavior and Incentives for Knowledge Subjects

By sharing useful knowledge with team members, knowledge subjects can jointly create the overall performance of the whole team. Therefore, knowledge sharing is the most important and effective way to reflect the value of knowledge and improve project performance[26] (Blohm et al. 2010). As a result, many companies have begun to develop a widely used knowledge management practice to create a sharing atmosphere through the use of incentives. Material means firstly attract the attention of scholars [27-28](Hedberget al. 2016; Camille et al. 2017;). Building on this logic, Seo et al. [29](2016), Hsu et al. [30] (2007) found that the main motives of knowledge sharing behaviors are subjective factors such as personal expectations, member trust, risk aversion. Hao et al.[31] (2016) considered the knowledge sharing behavior in the crowdsourcing contest, designed the knowledge sharing incentive mechanism in the crowdsourcing community based on game theory in order to study the relationship between knowledge sharing effort and answering effort. The basic model of this paper is similar to Hao’s paper, but we further explore the influencing factors of the knowledge sharing degree, and deeply analyse its impact on the crowdsourcing performance and the economic benefits [31] (Hao et al. 2016).

Psychological Characteristics of Fairness Concern

A sense of fairness is a key factor in determining the level of knowledge sharing effort. Individuals not only pay attention to their own interests in the process of knowledge sharing, but also care about the benefit and distribution fairness of others

[32](Samuelson 1993). The fairness preference utility functions mainly include distribution fairness represented by FS utility function[33] (Fehr and Gachter 2000) . In principal-agent theory, the horizontal fairness represented by the income among similar agents has certain universality [34](Karagozoglu and Keskin, 2018), but most practice shows the vertical fairness preference represented by the interest comparison between principal and agent is more representative. Vertical fairness concern is now more widely used in the pricing decision of supply chain[35-37] (Caliskan 2010; Du and Du 2010; Guo and Jiang 2016). Some literature has begun to focus on this issue in corporate incentive mechanism. Studies have shown that when employees envy their employers, their jealousy (vertical fairness concern) tightens their participation constraints and requires higher profit distribution[38](Englmaier and Wambach 2005); Li et al.[39] (2016) introduce retailer's vertical fairness concerns into the encroachment problem and explore its impact. It is shown that encroachment may be detrimental to the supplier when the retailer has strong fairness concerns and a significant marketing advantage. This paper introduces the vertical fairness concern of the crowdsourcee in the field of crowdsourcing innovation, trying to analyse the impact of this psychology on the cooperative and competitive relationship among knowledge subjects, and also explores in depth whether the crowdsourcer can overcome the negative effects of the fairness concern through optimized knowledge sharing incentives.

Aims, Contributions and Organizations of this Paper

From the above literature review, it can be seen that most of the existing relevant researches focus on the innovation effort input under the crowdsourcing contest, and rarely discuss the knowledge sharing behavior and incentive mechanism among in the crowdsourcing community, especially the literature considering the fairness concern of the crowdsourcees. This seems to have some gap with practice. Therefore, this paper aims to explain the internal mechanism of collaborative relationship among the crowdsourcees due to knowledge sharing, and to clarify the relationship between the psychology of fairness concern, behavior of knowledge sharing and performance of crowdsourcing projects. It overturns our traditional impression of the pure competitive relationship among the crowdsourcees in the existing research and expands the application scope of principal-agent theory and psychological contract theory. In practice, it provides reference for crowdsourcing organizers to effectively increase knowledge sharing behavior in the community and improve crowdsourcing project performance through the design of incentive mechanism and guidance of fairness concern.

The rest of the paper is organized as follows. The third part carries out the basic description of the model, constructs and solves the decision-making modes NKS (no knowledge sharing incentive) and KS (knowledge sharing incentive) and obtains the optimal value expression of decision variables and performance variables. The fourth part is the mathematical analysis of the results. Through the sensitivity analysis, we explore the behavior decisions and the crowdsourcing performance, discuss and compare how the economic benefits of both sides are affected by vertical fairness concern. Furthermore, we reveal the impact of the vertical fairness concern on the value of the knowledge sharing incentive mechanism through a comparative analysis. The fifth part is numerical simulation which verifies some of the conclusions and further explores the impact of knowledge sharing incentives, fairness concern on the economic benefits and value of the crowdsourcer. Closing off with a conclusion summary and management inspiration statement.

Model

Problem Description and Assumptions

We consider a creative crowdsourcing community in which the crowdsourcer publishes a creative project task, and n crowdsourcees participate in the task in a competitive way. Different from the generally competitive crowdsourcing platform, this community provides a convenient communication channel for knowledge sharing among the crowdsourcees and it contributes to the increase of the knowledge stock, which can not only improve the task performance but also reduce the cost of solutions. The crowdsourcer decides the winner according to the quality of the solutions submitted by each crowdsourcee, and awards the winner with the amount of A, which reflects the relationship of both competition and collaboration among the crowdsourcees.

The crowdsourcee i 's efforts are divided into two parts: private solution effort e_i and knowledge sharing effort s_i . According to Terwiesch and Yi[18](2008), we assume the private solution effort can improve the quality of the submitted solution by

$\eta_i \ln e_i$ with the cost $C(e_i) = c_e e_i$, where η_i is called the conversion rate of private effort performance which represents the knowledge, experience and ability of the crowdsourcee. On the other hand, the crowdsourcee i makes the knowledge sharing effort s_i through online communication, interactive discussion and other ways to improve the knowledge stock of the community. In view of the multiplicative effect of knowledge subject[9], the level of knowledge stock in crowdsourcing community can be expressed as $S = \prod s_j^{\alpha}$ ($0 < \alpha < 1$), in which α is the proportion of knowledge input of each crowdsourcee. It is obvious that when the crowdsourcees are homogeneous, we get $\alpha = 1/n$. According to Blohm et al.[26] (2010), the crowdsourcing project performance improved by knowledge stock can be expressed as $\beta_i S$, while the level of private solution effort cost reduced by knowledge stock is $c_e k_i S$ of which β_i is called the performance conversion rate and k_i the private effort cost reduction rate. We also assume that the crowdsourcee *i* pays a knowledge sharing effort cost of $h_i s_i^2 / 2$.

For a creative crowdsourcing project, the performance level v_i of the solution submitted by crowdsourcee i is detemined by its own experience and ability, the level of private solution effort, the community's knowledge stock and random factors [31](Hao et al. 2016). So, we can achieve:

$$v_i(e_i, s_i, \varepsilon_i) = \eta \, ln \, e_i + \beta_i \prod_{j=1}^{n} s_j^{\frac{1}{n}} + \varepsilon_i \tag{1}$$

ε_i is a random item, which indicates the uncertainty in the selection of solutions due to the different interests and hobbies of the crowdsourcer. We suppose ε_i obeys the

Gumble distribution with a median value of 0 and a scale of u. According to Hao et al.[31] (2016), the winning probability of crowdsourcee *i* can be expressed as follows:

$$P\left(v_i\left(e_i,s_i,\varepsilon_i\right)>max\left(v_j\left(e_j,s_j,\varepsilon_j\right)\right)\right)=\frac{exp\left(\eta ln e_i+\beta\prod_{j=1}^{n}s_j^{\frac{1}{n}}\right)}{\sum_{j=1}^{n}exp\left(\eta ln e_j+\beta\prod_{j=1}^{n}s_j^{\frac{1}{n}}\right)} \tag{2}$$

We assume that all crowdsourcees have vertical fairness concern. Referring to the research of Du and Du[36] (2010), the decision-making objective of subjects with fairness concern is utility maximization. The utility formula is

$$U_i=\pi_i+\lambda_i\left(\pi_i-\pi_f\right) \tag{3}$$

λ_i $\left(0<\lambda_i<1\right)$ is called vertical fairness concern coefficient which indicates the sensitivity of the fairness concern psychology of crowdsourcee *i*. $\left(\pi_i-\pi_f\right)$ shows the revenue gap between the crowdsourcee and the crowdsourcer. When $\pi_i>\pi_f$, fairness concern is manifested as “pride”, and the psychological utility increases; When $\pi_i<\pi_f$, fairness concern is embodied as “jealousy”, and the expected psychological utility decreases. Other important assumptions used in this paper are as follows:

· All the crowdsourcees are homogeneous, with the same shared knowledge performance conversion rate, the same shared knowledge solution cost reduction rate, the same shared knowledge cost coefficient, and the same vertical fairness concern coefficient, i.e. $\beta_1=\beta_2=\ldots=\beta_n=\beta$, $k_1=k_2=\ldots=k_n=k$, $h_1=h_2=\ldots=h_n=h$, $\lambda_1=\lambda_2=\ldots=\lambda_n=\lambda$.

· The actual crowdsourcing project performance obtained by the crowdsourcer is expressed by the expected project performance contributed by the winning crowdsourcee.

· Decision-making of both sides is a stackelberg game process where the crowdsourcer is the game leader and the crowdsourcees are the followers among whom it is a static game.

· All the content in the crowdsourcing community is open, so all the above information is common knowledge.

Obviously, under the assumption of homogeneity, all private solution efforts and knowledge sharing efforts of the crowdsourcees must be the same. Thus, Formula (2) - the winning probability of *i* can be further expressed as

$$P\left(v_i\left(e_i,s_i,\varepsilon_i\right)>max\left(v_j\left(e_j,s_j,\varepsilon_j\right)\right)\right)=\frac{1}{1+\left(n-1\right)exp\left(\frac{\eta\left(lne-lne_i\right)}{u}\right)} \qquad (4)$$

In Formula (4), e is the general term for the private solution efforts. Thus, we can see that increasing the knowledge sharing effort cannot improve the winning probability of crowdsourcees if they have the same shared knowledge performance conversion rate.

For the crowdsourcer, its benefit is determined by the crowdsourcing performance submitted by the winning crowdsoucee, and its cost is the project bonus. So the expected net revenue of the crowdsoucee can be expressed as:

$$\pi_f = \sum_{i=1}^{n} \frac{\left(\eta \, ln\, e_i + \beta_i \prod_{j=1}^{n} s_j^{\frac{1}{n}}\right)}{1+(n-1)exp\left(\frac{\eta(ln\, e - ln\, e_i)}{u}\right)} - A - F(s_k) \tag{5}$$

In the above formula, the first item is the project performance, i.e. the expected revenue of the crowdsourcer, which is the weighted sum of each crowdsoucee's winning probability and the performance of the solution provided, the second item is the bonus set by crowdsoucer for every crowdsourcing contest project, and the third item is the knowledge sharing reward which is zero when the knowledge sharing incentive mechanism is not implemented.

Model 1: Decision-making without Knowledge Sharing Incentive (NKS)

According to the above description, the expected revenue of the crowdsoucee *i* is consisted only of the project bonus when there is no knowledge sharing incentive. It can be expressed as

$$\pi_i = \frac{A}{1+(n-1)exp\left(\frac{\eta(ln\, e - ln\, e_i)}{u}\right)} - c_e\left(e_i - k\prod_{j=1}^{n} s_j^{\frac{1}{n}}\right) - \frac{1}{2}hs_i^{\,2} \tag{6}$$

The crowdsoucer's expected revenue is shown in Formula (5), where $F(s_k) = 0$. Thus, we can derive the crowdsoucee *i*'s expected utility function under the vertical fairness concern according Formula (3), that is:

$$U_i = (\lambda+1)\left(\frac{A}{1+(n-1)exp\left(\frac{\eta(ln e - ln e_i)}{u}\right)} - c_e\left(e_i - k\prod_{j=1}^{n} s_j^{\frac{1}{n}}\right) - \frac{1}{2}hs_i^{\ 2}\right)$$
$$-\lambda\left(\sum_{i=1}^{n}\frac{\left(\eta ln e_i + \beta\prod_{j=1}^{n} s_j^{\frac{1}{n}}\right)}{1+(n-1)exp\left(\frac{\eta(ln e - ln e_i)}{u}\right)} - A\right) \quad (7)$$

According to the Assumption (4), the decision sequence is: (1) the crowdsourcer decides the project bonus A; (2) the crowdsoucee decides its private solution effort e_i and knowledge sharing level s_i. Lemma 1 summarizes the equilibrium results of the model NKS. All the proofs are presented in the Appendix.

Lemma 1: When the knowledge sharing incentive mechanism is not implemented, the expression of optimal private solution effort of the crowdsoucee when the project bonus is fixed and is variable, the optimal level of knowledge sharing, the crowdsoucee's expected economic revenue, the project bonus set by the crowdsoucer, the crowdsoucer's expected economic revenue, the expected project performance are as follows respectively:

$$e_i^{NKS-} = \frac{\eta\left((\lambda+1)(n-1)A - \lambda un^2\right)}{(\lambda+1)uc_e n^2}, e_i^{NKS*} = \eta^2(\lambda+1)(n-1), s_i^{NKS*} = \frac{(\lambda+1)kc_e - \lambda\beta}{(\lambda+1)nh}$$
$$\pi_i^{NKS^*-} = \frac{\left(kc_e(\lambda+1)(2n-1)+\lambda\beta\right)\left(kc_e(\lambda+1)-\lambda\beta\right)}{2n^2h(\lambda+1)^2} + \frac{un\left(\eta(\lambda+1)^2(n-1)c_e+\lambda\right)}{(\lambda+1)(n-1)}$$
$$-\eta^2 c_e(\lambda+1)(n-1)$$
$$A^{NKS*} = \frac{\eta(\lambda+1)^2 un^2(n-1)c_e + \lambda un^2}{(\lambda+1)(n-1)} \quad (8)$$
$$\pi_f^{NKS^*} = \eta\, ln\left(\eta^2(\lambda+1)(n-1)\right) + \frac{\beta\left((\lambda+1)kc_e - \lambda\beta\right)}{(\lambda+1)nh} - \frac{un^2\left(\eta(\lambda+1)^2(n-1)c_e+\lambda\right)}{(\lambda+1)(n-1)}$$
$$E\left(v^{NKS^*}\right) = \eta\, ln\left(\eta^2(\lambda+1)(n-1)\right) + \frac{\beta\left((\lambda+1)kc_e - \lambda\beta\right)}{(\lambda+1)nh}$$

Model 2: Decision-making with knowledge sharing incentive (KS)

This section considers the model of implementing knowledge sharing incentive mechanism in the crowdsourcing community. The mechanism is described as follows: in the sharing area (such as BBS), the crowdsourcer carefully observes the extent to which the crowdsourcee discloses valuable knowledge and the frequency of communication, analyses the correlation among the exchanged contents, and determines the observable degree of its knowledge sharing behavior θ_i (we can get $\theta_1 = \theta_2 = ... = \theta_n = \theta$ from the assumption of homogeneity) , and the crowdsourcer accordingly gives them the unit reward at level *b*. Therefore, crowdsourcee *i* can get the knowledge sharing benefit of $b\theta s_i$. Since *b* affects the incentive cost of the crowdsourcer as well as the knowledge sharing level, there must be a game relationship between them. We know that the shared knowledge does not change the winning probability of the crowdsourcee, so it is still as shown in Formula (6). Figure 1 describes the main process of the knowledge sharing incentive mechanism.

ADD FIGURE 1. HERE ABOUT

We can get the expected revenue of crowdsourcee *i* under knowledge sharing incentive mechanism:

$$\pi_i = \frac{A}{1+(n-1)exp\left(\frac{\eta(ln\,e - ln\,e_i)}{u}\right)} + b\theta s_i - c_e\left(e_i - k\prod_{j=1}^{n} s_j^{\frac{1}{n}}\right) - \frac{1}{2}hs_i^{\,2} \tag{9}$$

And the expected revenue of the crowdsourcer is

$$\pi_f = \sum_{i=1}^{n} \frac{\left(\eta \ln e_i + \beta_i \prod_{j=1}^{n} s_j^{\frac{1}{n}} \right)}{1 + (n-1) exp\left(\frac{\eta (\ln e - \ln e_i)}{u} \right)} - A - nb\theta s_i \tag{10}$$

Similar to the model NS, the *i*'s expected utility function under the vertical fairness concern can be expressed as

$$\begin{aligned} U_i = (\lambda+1) & \left(\frac{A}{1 + (n-1) exp\left(\frac{\eta (\ln e - \ln e_i)}{u} \right)} - c_e \left(e_i - k \prod_{j=1}^{n} s_j^{\frac{1}{n}} \right) - \frac{1}{2} h s_i^2 + b\theta s_i \right) \\ & - \lambda \left(\sum_{i=1}^{n} \frac{\left(\eta \ln e_i + \beta \prod_{j=1}^{n} s_j^{\frac{1}{n}} \right)}{1 + (n-1) exp\left(\frac{\eta (\ln e - \ln e_i)}{u} \right)} - A - nb\theta s_i \right) \end{aligned} \tag{11}$$

The game order can be described as: (1) the crowdsourcer decides the project bonus A; (2) the crowdsourcee decides the linear unit knowledge sharing reward *b*; (3) the crowdsourcee decides its private solution effort e_i and knowledge sharing level s_i Lemma 2 summarizes the equilibrium results of the model KS. All the proofs are presented in the Appendix.

Lemma 2: When the incentive mechanism of knowledge sharing is implemented, the expression of the optimal private solution effort of the crowdsoucee when the project bonus is fixed and is variable, the optimal level of knowledge sharing, the crowdsourcee's expected revenue, the optimal project bonus, the optimal linear unit knowledge sharing reward , the crowdsourer's expected revenue, and the expected project performance are as follows respectively:

$$
\begin{aligned}
&e_i^{KS-} = \frac{\eta\left(\left(\lambda+1\right)\left(n-1\right)A-\lambda un^2\right)}{\left(\lambda+1\right)uc_e n^2}, e_i^{KS*} = \eta^2\left(\lambda+1\right)\left(n-1\right), s_i^{KS*} = \frac{\left(\lambda+1\right)kc_e+\left(n\lambda+1\right)\beta}{2\left(\lambda+1\right)nh} \\
&\pi_i^{KS^*} = b^{KS*}\theta s_i^{KS*} + kc_e s_i^{KS*} - \frac{hs_i^{KS*2}}{2} + \frac{un\left(\eta\left(\lambda+1\right)^2\left(n-1\right)c_e+\lambda\right)}{\left(\lambda+1\right)\left(n-1\right)} - \eta^2 c_e\left(\lambda+1\right)\left(n-1\right) \\
&A^{KS*} = \frac{\eta\left(\lambda+1\right)^2 un^2\left(n-1\right)c_e+\lambda un^2}{\left(\lambda+1\right)\left(n-1\right)}, b^{KS*} = \frac{\left(\left(n+2\right)\lambda+1\right)\beta-\left(\lambda+1\right)kc_e}{2\left(\left(n+1\right)\lambda+1\right)n\theta} \\
&\pi_f^{KS^*} = \eta\, ln\left(\eta^2\left(\lambda+1\right)\left(n-1\right)\right) + \frac{\beta\left(\left(\lambda+1\right)kc_e-\lambda\beta\right)}{\left(\lambda+1\right)nh} - \frac{un^2\left(\eta\left(\lambda+1\right)^2\left(n-1\right)c_e+\lambda\right)}{\left(\lambda+1\right)\left(n-1\right)} \\
&\qquad + \frac{\left(\left(\left(n+2\right)\lambda+1\right)\beta-\left(\lambda+1\right)kc_e\right)^2}{4\left(\lambda+1\right)\left(\left(n+1\right)\lambda+1\right)nh} \\
&E\left(v^{KS^*}\right) = \eta\, ln\left(\eta^2\left(\lambda+1\right)\left(n-1\right)\right) + \frac{\beta\left(\left(\lambda+1\right)kc_e+\left(n\lambda+1\right)\beta\right)}{2\left(\lambda+1\right)nh}
\end{aligned}
\tag{12}
$$

Main Results

We now explore the impact of the vertical fairness concern on the conditions for establishing the knowledge sharing incentive mechanism, and its influence on the input of private efforts, the level of knowledge sharing, expected project performance and the estimated revenue of the crowdsourcer. We also study in detail the economic value of the knowledge sharing incentive mechanism. Propositions are as follows.

Proposition 1. When the knowledge sharing incentive is not implemented: (1) Only when the project bonus A is above the threshold $\lambda un^2/\left(\lambda+1\right)\left(n-1\right)$, the crowdsourcee is willing to participate in the crowdsourcing project, while the threshold is positively related to λ; (2) only when the ratio (β/k) between the performance improvement rate, and the cost reduction rate of private solution brought by shared knowledge, is below the threshold $\left(\lambda+1\right)c_e/\lambda$, that the crowdsourcee is willing to share knowledge, and the threshold is negatively related to λ.

The proposition shows that when the crowdsourcee has vertical fairness concern, the crowdsourcing contest project bonus should not be set too low, which matches our intuition that Zhubajie.com requires the prize for each competition item be no less than RMB500. Whether the crowdsourcee is willing to share knowledge is not related to the project bonus, but to the ratio of performance improvement rate and solution cost reduction rate. Only when the ratio is below a certain threshold can knowledge stock significantly reduce the cost of private solutions, the crowdsourcee then has the motivation to share knowledge. We also find that the greater the sensitivity of fairness concern, the lower the threshold, and the crowdsourcee is less likely to share knowledge.

Proposition 2. (1) Only when the ratio β / k is higher than $\frac{(\lambda+1)c_e}{(n+2)\lambda+1}$, the crowdsourcer will implement the knowledge sharing incentive mechanism, and the threshold is negatively related to λ. (2) Under the knowledge sharing incentive mechanism, the crowdsourcee must be willing to share knowledge.

The proposition shows that for the crowdsourcer, the knowledge sharing incentive mechanism is only implemented when the knowledge sharing performance improvement rate is higher than a certain threshold, otherwise it will be abandoned because of the excessive incentive cost. In addition, the higher the sensitivity of vertical fairness concern, the lower the crowdsourcer's requirement for the performance improvement rate, leading to greater probability of implementing the incentive mechanism because the crowdsourcee is more mindful of the revenue gap. From this perspective, vertical fairness concern helps to improve the status of the crowdsourcee in the game. Once the incentive mechanisms are implemented, the crowdsourcee is willing to share the knowledge unconditionally, which is significantly different from the findings in Proposition 1 where there is no implementation of incentive mechanism.

Proposition 3. When the incentive mechanism condition is established, b^{KS*} is positively correlated to λ and β, negatively correlated to k and θ. When β / k is larger, b^{KS*} is negatively correlated to n; when β / k is smaller, b^{KS*} is negatively correlated to n.

The proposition expounds the influencing factors of the optimal linear unit reward in knowledge sharing set by the crowdsoucer. Firstly, it is positively correlated with the sensitivity of the vertical fairness concern. As shown in Proposition 4.1, the stronger bargaining power gained by vertical fairness concern must stimulate the crowdsourcer to increase the knowledge sharing incentive and ensure the projects performance. Secondly, the knowledge sharing performance improvement rate will enhance the unit reward, while the solution cost reduction rate will play a negative role. It is worth noting that the knowledge sharing frequency θ does not increase the level of knowledge sharing incentives, for the crowdsourcer could generate an opportunistic psychology of "stronger gets no rewards", and they believe that the crowdsourcee will share knowledge without any motivation. Finally, When the performance improvement rate is high, or the solution cost reduction rate is low, increasing the number of crowdsourcees will intensify the competition among them. Therefore, the crowdsourcer will reduce the rewards to save cost; conversely, it will highlight the vertical fairness concern effect, and the crowdsourcer has to increase the knowledge sharing rewards.

Proposition 4. (1) $A^{KS*} = A^{NKS*}$, A^{KS*} is positively related to λ and n; (2) $e_i^{KS-} = e_i^{NKS-}$, $e_i^{KS*} = e_i^{NKS*}$, e_i^{NKS-} is negatively related to λ , e_i^{KS*} is positively related to λ and n.

The proposition shows that the optimal crowdsourcing project bonus set by the crowdsourcer and the crowdsourcee’s private solution effort, are not related to whether the knowledge sharing incentive mechanism is implemented. The crowdsourcee does not have to worry about receiving their bonus because of sharing knowledge. If the bonus of a crowdsourcing project is fixed, the degree of private effort is declined with vertical fairness concern. However, when the bonus is variable, the crowdsoucer will certainly increase the bonus, because of the existence of fairness concern, which will stimulate crowdsourcees to put more solution efforts. In addition, as the number of crowdsourcees continues to increase, they will improve private solution efforts due to the competitive effect regardless of the sensitivity of the fairness concern. That is why more crowdsourcing platforms (such as Innocentive and Zhubajie) use variable bonuses to attract more crowdsourcees to join.

Proposition 5. When the incentive mechanism condition is met, (1) $s_i^{NKS*} > 0$, s_i^{NKS*} is negatively related to λ ; (2) s_i^{KS*} is positively related to λ ; (3) $\left(s_i^{KS*} - s_i^{NKS*}\right) > 0$ and is positively related to λ ; when $\beta / kc_e < \frac{\lambda + 1}{2\lambda + 1}$, $\left(s_i^{KS*} - s_i^{NKS*}\right)$ is negatively related to n; otherwise, $\left(s_i^{KS*} - s_i^{NKS*}\right)$ is negatively related to n.

We can see from the proposition that even knowledge sharing incentives are not implemented, crowdsourcee will still share knowledge for the purpose of reducing private effort cost, which is quite different from Hao et al.[31] (2016). But the level of knowledge sharing is negatively correlated with the sensitivity of vertical fairness concern. The reason is that, the higher the knowledge stock, the greater the project performance which should bring larger benefits to the crowdsourcer. It will ineluctably lead to an envy psychology of the crowdsourcee, and a significant decrease in knowledge sharing when they anticipate the above situation. When the knowledge sharing incentive is implemented, the conclusion will be the opposite. The crowdsourcer will increase unit knowledge sharing reward b with vertical fairness concern according to Proposition 4. 2, the utility loss of the crowdsourcee will be compensated.

The proposition also shows that the increment effect of the knowledge sharing incentive mechanism will expand with the vertical fairness concern. However, whether the crowdsourcee's number will help the increment of knowledge sharing depends on the ratio β / k . When the ratio is high, the dominant effect of knowledge sharing behavior (for the improvement of project performance) is greater than the hidden effect (for the reduction of private cost). The envy psychology accumulated will reduce their knowledge sharing effort; when the ratio is low, the hidden effect is higher than the dominant effect, and the cumulative "proud" psychology will increase knowledge sharing effort.

Proposition 6. When the incentive mechanism condition is met, (1) if $\frac{\eta}{\beta^2} > \frac{1}{hn}$, $E\left(v^{NKS*}\right)$ is necessarily positively related to λ ; if $\frac{\eta}{\beta^2} < \frac{1}{2hn}$, $E\left(v^{NKS*}\right)$ is necessarily negatively related to λ ; (2) $E\left(v^{KS*}\right)$ must be positively correlated with λ ; (3) $E\left(v^{KS*}\right) > E\left(v^{NKS*}\right)$, $\left(E\left(v^{KS*}\right) - E\left(v^{NKS*}\right)\right)$ is always positively related to λ; when $\beta < kc_e$, $\left(E\left(v^{KS*}\right) - E\left(v^{NKS*}\right)\right)$ is positively correlated with *n*; conversely, they are negatively related.

This proposition describes the impact of the vertical fairness concern's sensitivity of the crowdsourcee on the expected performance of the crowdsourcing project. Specifically speaking, when the knowledge sharing incentive mechanism is not implemented, the relationship between the expected performance level, and the sensitivity of fairness concern depends on the ratio between the conversion rate of private effort performance and the square of the conversion rate of shared knowledge performance (η / β^2). When the ratio is high, it indicates that the improvement effect of private solution efforts on performance, is more obvious than the shared knowledge stock. The vertical fairness concern is beneficial to increase the performance by enhancing the private solution input. When the ratio is low, the jealousy of the crowdsourcee will weaken the level of knowledge sharing. Therefore, the project performance is negatively correlated with the vertical fairness concern. However, under the knowledge sharing incentive mechanism, the rewards obtained from the mechanism enhancing their motivation of knowledge sharing. As a result, the two types of efforts and expected performance are both improved.

Finally, we can say that the degree of performance increment produced by incentive mechanism has always increased with the fairness concern sensitivity. Further, whether the crowdsourcee's number contributes to the project performance value depends on the ratio β / k. This is contrary to some classical literature on crowdsourcing such as Howe[11](2008), who believed the advantage of crowdsourcing is the crowd wisdom. Only when the ratio is low will the result be positive. Therefore, regardless of the relative or absolute performance improvement of the crowdsourcing project, implementing knowledge sharing incentive mechanisms and attracting more crowdsourcees with strong fairness concern should be the best choice for the crowdsourcer.

Proposition 7. When the incentive mechanism condition is established: (1) $\pi_f^{KS*} > \pi_f^{NKS*}$, and $\left(\pi_f^{KS*} - \pi_f^{NKS*}\right)$ is always positively related with λ; when $\frac{\beta}{k} < \frac{(\lambda+1)\left((2n+1)\lambda+1\right)c_e}{\left((\lambda+1)\left((n+1)\lambda+1\right)+n\lambda^2\right)}$, $\left(\pi_f^{KS*} - \pi_f^{NKS*}\right)$ is positively correlated with n, conversely, they are negatively related; (2) when $c_e > \frac{1}{(\lambda+1)un^2}$, π_f^{NKS*} is always negatively related to λ; when $c_e < \frac{1}{(\lambda+1)un^2}$, if the condition $\eta > \frac{(n-1)\beta^2 + un^3 h}{(\lambda+1)n(n-1)h\left(1-c_e(\lambda+1)un^2\right)}$ is met, π_f^{NKS*} and π_f^{KS*} are positively related to λ; otherwise, π_f^{NKS*} is negatively related to λ.

The proposition shows that the crowdsourcer always has the economic motivation to implement the knowledge sharing incentive. Moreover, with the increase of vertical fairness concern sensitivity, the impact of knowledge sharing incentive mechanism on the crowdsourcer's ecomomic value (i.e. relative revenue increment) is also increasing. That is to say, the vertical fairness concern can simultaneously achieve Pareto improvement on the project performance and the relative economic benefits of knowledge sharing. However, the increase of the number of crowdsourcees places uncertainty on the role of knowledge sharing in stimulating economic value. Due to the impact of vertical fairness concern, only when the knowledge sharing performance conversion rate is relatively lower than the private solution cost reduction rate, must it be effective for crowdsourcer to expand the size of crowdsourcing communities.

On the other hand, if the economic benefits generated by the private solution efforts are taken into account, the vertical fairness concern does not necessarily benefit the absolute expected gains of the crowdsourcer. Only when the crowdsourcee has a higher problem-solving ability, can the absolute economic benefit of the crowdsourcer in NKS mode increase accordingly. Otherwise, although the knowledge sharing incentives are economical, it is unable (at least in NKS mode) to use vertical fairness concern to increase economic revenue due to the inefficiency of the private solution efforts.

Simulation and Discussion

In view of the complexity of the model results, this part mainly uses the numerical simulation method to study the economic benefits of the crowdsourcee and verify some of the above important propositions.

Referring to Hao et al. [31](2016), we set the basic numeric parameters as follows: $c_e = 0.2$, $h = 0.1$, $\mu = 2$. First, we explore the crowdsourcee's relative economic value generated by knowledge sharing incentive mechanism ($\pi_i^{KS*} - \pi_i^{NKS*}$). Without the loss of generality, we set the conversion rate of private effort performance at $\eta = 0.8$, and then select two cases of (1) $\beta = 0.4, k = 0.2$ and (2) $\beta = 0.1, k = 0.3$. The comparison figure is shown in Figure 2 and Figure 3.

ADD FIGURE 2. HERE ABOUT

ADD FIGURE 3. HERE ABOUT

It can be seen from Fig. 2 and Fig. 3 that all the curves are located above the 0 axis which indicates the incentive mechanisms generate positive value to the crowdsourcee, thus it helps to achieve a win-win situation for both parties. Comparing the two figures, we then disclose the regulated effect of ratio β / k . When β / k is low (Fig. 2), the economic value curve is always obliquely upward, and the position of the curve with larger n is higher. This shows that when the dominant effect of the knowledge stock is lower than the hidden effect, the "proud" psychology can promote crowdsourcee's higher knowledge sharing behavior which brings them greater economic value by improving project performance. In this case, the more the crowdsourcees, the stronger the crowdsourcee's bargaining power and the higher the economic value of knowledge sharing. However, when η / β is higher (Fig. 3), the result will be opposite. We can see that curves all rise first and then fall, except when $n = 5$. This means that when the dominant effect is greater than the hidden effect, the external manifestation of vertical fairness concern will definitely be "envy". Although the knowledge sharing behavior is enhanced by incentive, it is only a passive action which has limited effect and cannot offset the knowledge sharing cost. Therefore, when the sensitivity of fairness concerns is relatively high, the economic value will show a downward trend. In this case, the increase in the number of crowdsourcees also means an increase in competition and a weakening of the knowledge sharing behavior. This is similar to the change in the value of the crowdsourcer.

Now we will discuss the total absolute expected economic gain of crowdsourcees included project bonus. Firstly, we set $n = 8$, analyse the influence of λ on π_i^{KS*} under different η / β values. And then fixing $\eta = 0.5, \beta = 0.4$, we obtain the trend graph of π_i^{KS*} changing with n under different λ, as shown in Figure 4 and Figure 5.

ADD FIGURE 4. HERE ABOUT

ADD FIGURE 5. HERE ABOUT

It can be seen from Figure 4 that regardless the ratio η / β , the existence of vertical fairness concern must help to improve the absolute economic gain, which is obviously different from relative value. But when the fairness concern is certain, the increasing of η / β is conducive to promote economic gain. This matches the rules of project bonus and implies that trying to be the winner of the crowdsourcing contest is still the main revenue source for the crowdsourcee. No matter how the sensitivity of fairness concern changes, the absolute economic gain must be positively correlated with the number of crowdsourcees. Further, we can see the vertical fairness concern is also conducive to increasing the marginal contribution of crowdsourcee numbers from the greater curves slope in Figure 5.

Conclusions and Implications

Conclusions

Crowdsourcing is recognized as an important innovation issue facing all kinds of enterprises and the society at this time, and the knowledge sharing is of great significance to the crowdsourcing community. In this paper, an incentive mechanism for knowledge sharing is designed when the crowdsourcee has vertical fairness concern. **Along the line of innovation efforts to crowdsourcing performance to economic benefits,** we use the game theory to establish and solve the non-knowledge sharing incentive model (NKS) and knowledge sharing incentive model (KS), and further discuss the impact of the vertical fairness sensitivity on the private solution effort, knowledge sharing level, project performance and economic interests of both sides. We have got some solid and meaningful conclusions from the research.

Firstly, though knowledge sharing helps to reduce the crowdsourcee's cost of private solution, it can't improve its winning probability in crowdsourcing contest because each crowdsourcee benefits the same from it. As a result, the KS mechanism will only be workable if ratio β / k is within a certain range. If the ratio is too high, the private cost reduction obtained can't promote the crowdsourcees to share knowledge while the incentive mechanism will be abandoned by crowdsoucer because of the excessive incentive cost if the ratio is too low. When the condition is met, crowdsourcees will spontaneously share knowledge because of the private cost reduction even if there is no incentive. This is quite different from the results of Hao et al. [31](2016) who believe that knowledge sharing behavior can only be generated under the stimulation. For the same reason of winning probability, we can say that the implementation of KS mechanism will neither increase the project bonus, nor increase the degree of the private solution effort.

Secondly, we find the important role of crowdsourcees' fairness concern plays in crowdsourcing community. If knowledge sharing incentive mechanism is not implemented (i.e. model NKS), the level of knowledge sharing will significantly decrease with fairness concern for it should bring larger benefits to the crowdsourcer and will ineluctably lead to an envy psychology of the crowdsourcees. When knowledge sharing incentive mechanism is implemented (i.e. model KS), vertical fairness concern will lead to high knowledge sharing behavior thanks to the increasing of unit knowledge sharing reward. It is good to see that when crowdsourcees fairness concern become more sensitive, the private effort of the crowdsourcee increases in variable project bonus all the time. Because only "private" factors can really promote the winning probability in crowdsourcing contest and meet their "proud" psychology, which is line with the conclusions of Li et al.[39] (2016).

Thirdly, the crowdsourcing project performance is the most attractive indicator in crowdsourcing innovation and is determined by the crowdsourcee's private solution effort and the shared knowledge stock, so KS model is more conductive to it than NKS model undoubtedly. But the relationship of the project performance with fairness concern sensitivity and the number of crowdsourcees remain uncertain. As mentioned above, in model KS, private and knowledge sharing effort are all positively with fairness concern sensitivity, so it will definitely improve project performance. However, in model NKS, the ratio η / β plays a regulatory role due to the opposite effect of fairness concern on the two efforts. Only when the ratio is enough high, which indicates effect of private solution efforts on performance is more obvious than the shared knowledge stock, can performance be driven by fairness concern. Furthermore, the biggest advantage of crowdsourcing innovation has been cited to be the scale [11,14,31](Howe 2008; Feyisetan and Simperl 2017; Hao et al. 2016). But we find the influence of the crowdsourcee numbers on project performance depends on the ratio β / k if crowdsourcees have the psychology of fairness concern. The high values mean the dominant effect of knowledge sharing (i.e. the effect of performance improving which is good for crowdsourcer) is obvious. In this case, vertical fairness concern is manifested as "jealousy", and the increase of crowdsourcee numbers is not conducive to the project performance; on the contrary, the result is opposite as the hidden effect (i.e. the effect of private effort cost reduction which is good for themselves) is obvious, and the fairness concern is more manifested as "pride".

Finally, from the perspective of economy, the incentive mechanism of knowledge sharing can achieve a win-win situation for both sides. This shows that no matter for the crowdsourcer or the crowdsourcees, the benefits from the incentive mechanism of knowledge sharing are higher than the cost of their expenditure. We also find the value caused by knowledge sharing incentive mechanisms always increases with the improvement of the sensitivity of vertical fairness concern thanks to the crowdsourcer's response strategy mentioned before (increasing project bonuses and unit knowledge sharing reward). Moreover, the impact of crowdsourcee numbers on the relative value of knowledge sharing incentive mechanism depends on ratio β / k , which is line up with the rule of project performance. If the project bonus and the cost of private solution efforts are taken into account, we can say the results can be more complex. Because the crowdsourcees' private effort increase with the sensitivity of their vertical fairness concern, so, to the crowdsourcer, only when the coefficient of private solution cost is small and the performance conversion rate is high (i.e. the crowdsourcee has a higher problem-solving ability), does its total economic gain positively correlate with the vertical fairness concern. But to crowdsourcees, the vertical fairness concern must help raise their absolute economic gains in all circum. We think this is the embodiment of "backward advantage".

Implications

The conclusions provide useful implications to improve the performance of crowdsourcing contest innovation project.

The authors address how crowdsourcers should actively promote a knowledge sharing incentive mechanism. Specifically related to a knowledge sharing community (for example - an online forum or platform) where participants can exchange their professional knowledge and skills.

In addition, the authors explore how a knowledge sharing behavior evaluation system should be established online to effectively identify the part of shared knowledge that really leads to performance improvement and then use it as a reward benchmark.

Interesting discussions are made to discuss the importance for crowdsourcers to correctly treat the psychology of crowdsourcees' vertical fairness concern, and try to convert through mathematics complex emotional behaviors, such as the feeling of "pride" and "jealousy"

One interesting finding made, is that more attention should be paid to the evaluation the cost associated with online participants experience or skill-levels, to highlight the role of sharing knowledge in reducing private answering costs and improve its "recessive effect". The implementation of knowledge training system in the community is also discussed to review how the efficiency of crowdsourcees in transforming public knowledge into crowdsourcing performance. On this basis, crowdsourcers should project a "project bonus" to attract more participants and/or effectively expand the project's scope and outputs.

The aurthors close with a critical discussion, to consider how crowdsourcees have more professional skills but lower willingness to share knowledge (for example, the radio η / β is relatively high), then fairness concern psychology is not conducive to the improvement of knowledge stock and crowdsourcing performance. Therefore, the level of individual solution should not be the only criterion for the admission to the crowdsourcing contest. crowdsourcers should test their psychological characteristics when recruiting participants. If they are too jealous or conservative, they should be abandoned decisively. In addition, in the process of project, crowdsourcers should also maintain certain communication with the crowdsourcees, and guide them not to pay too much attention to the income gap.

Limitations and Future Research

Though the conclusions and implications show robust in the assumptions set forth in this paper, we still want to remind the readers not to freely apply our results to all situations. Only when the type of crowdsourcing is a creative contest, the performance formula is valid. However, in a professional crowdsourcing contest, the performance function and the winning probability will show a significant difference. Moreover, in this paper, we consider the homogeneity of crowdsourcees which does not correspond to the reality. In the future, we can further consider the heterogeneity between crowdsourcee and crowdsourcer. The impact of horizontal fairness concern among crowdsourcees on knowledge sharing incentive mechanisms will be also significant. The conclusions of this paper focus on theoretical analysis and numerical simulation and need to be further tested by empirical analysis.

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Figures

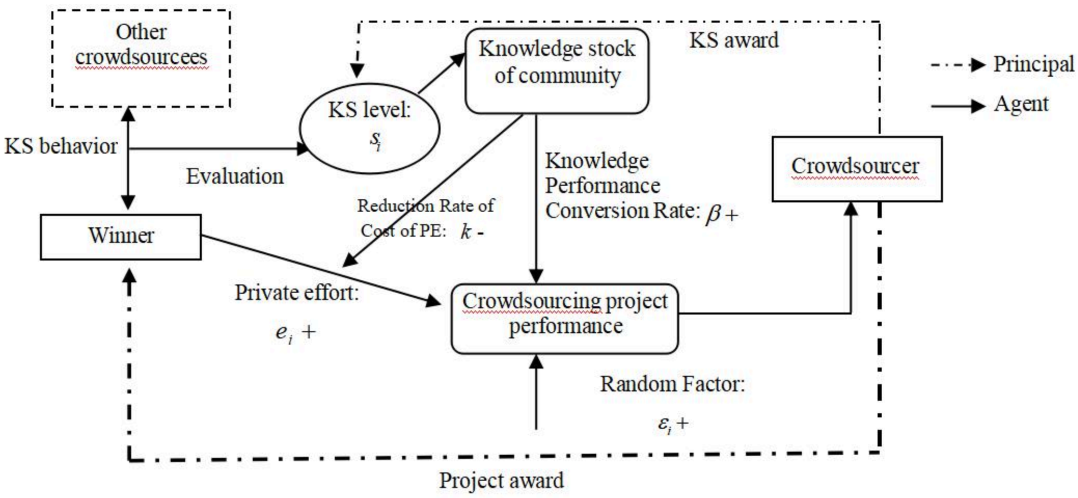

Figure1: Process of knowledge sharing incentive mechanism in crowdsourcing community

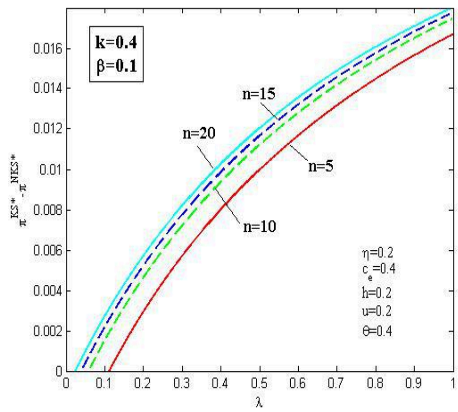

Figure 2: The impact of n and λ on $\pi_i^{KS} - \pi_i^{NKS}$ (low β / k)

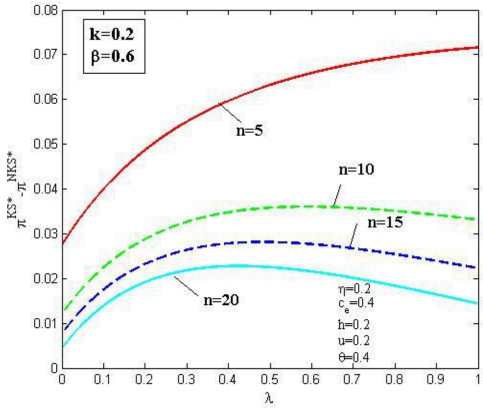

Figure 3: The impact of n and λ on $\pi_i^{KS} - \pi_i^{NKS}$ (high β / k)

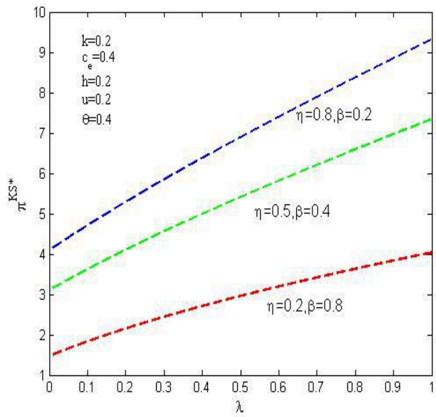

Figure 4: The impact of λ on π_i^{KS*}

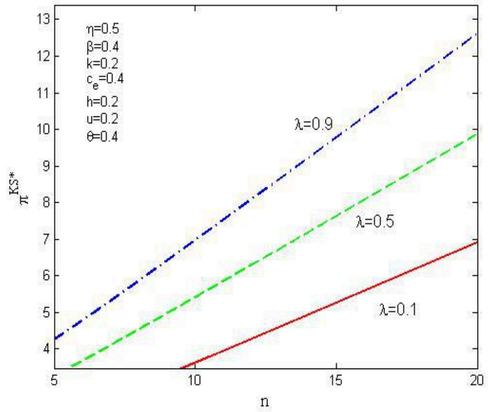

Figure 5: The impact of n on π_i^{KS*}

Appendix

Proof of Lemma 1

Considering crowdsourcer acts as a leader and crowdsourcees are the followers, we first solve out the decisions of the crowdsourcees. Taking the first partial derivatives of U_i with respect to e_i and s_i respectively, and substituting the symmetry strategy $e_1 = e_2 = ... = e_i = e_i^*$, $s_1 = s_2 = ... = s_i = s_i^*$ obtained from the homogeneity hypothesis, the following equations are obtained:

$$\begin{cases} \dfrac{\partial U_i}{\partial e_i} = \dfrac{(n-1)\eta(\lambda+1)A}{e_i un^2} - (\lambda+1)c_e - \dfrac{\lambda\eta}{e_i} = 0 \\ \dfrac{\partial U_i}{\partial s_i} = (\lambda+1)\left(\dfrac{kc_e}{n} - hs_i\right) - \dfrac{\lambda\beta}{n} = 0 \end{cases} \quad \text{(A1)}$$

Then, we get the pooling equilibrium

$$e_i^{NKS-} = \frac{\eta\left((\lambda+1)(n-1)A - \lambda un^2\right)}{(\lambda+1)uc_e n^2}, s_i^{NKS-} = \frac{(\lambda+1)kc_e - \lambda\beta}{(\lambda+1)nh} \quad \text{(A2)}$$

It is proved that if $A > \dfrac{\lambda un^2}{(\lambda+1)(n-1)}$ then $\dfrac{\partial U_i^2}{\partial^2 e_i} = -\dfrac{(n-1)\eta(\lambda+1)A}{e_i^2 un^2} + \dfrac{\lambda\eta}{e_i^2} < 0, \dfrac{\partial U_i^2}{\partial^2 s_i} = -(\lambda+1)h < 0$, which indicates that e_i^{NKS-} and s_i^{NKS-} is the optimal private solution effort and knowledge sharing level of the recipients under NKS mode. Substituting Formula (A2) back into Formula (1), (6) and (5), the expressions of project performance, expected economic benefit of the crowdsourcees and the crowdsourcer can be obtained as follows:

$$
\begin{aligned}
&E\left(v^{NKS\_}\right)=\eta\, ln\left(\frac{\eta\left((\lambda+1)(n-1)A-\lambda un^2\right)}{(\lambda+1)uc_e n^2}\right)+\frac{\beta\left((\lambda+1)kc_e-\lambda\beta\right)}{(\lambda+1)nh}\\
&\pi_i^{NKS\_}=\frac{\left(kc_e(\lambda+1)(2n-1)+\lambda\beta\right)\left(kc_e(\lambda+1)-\lambda\beta\right)}{2n^2h(\lambda+1)^2}+\frac{A}{n}\left(1-\frac{(\lambda+1)(n-1)\eta}{(\lambda+1)un}\right)+\frac{n\lambda}{\lambda+1}\\
&\pi_f^{NKS\_}=\eta\, ln\left(\frac{\eta\left((\lambda+1)(n-1)A-\lambda un^2\right)}{(\lambda+1)uc_e n^2}\right)+\frac{\beta\left((\lambda+1)kc_e-\lambda\beta\right)}{(\lambda+1)nh}-A
\end{aligned}
\tag{A3}
$$

According to $\partial\pi_f^{NKS\_}/\partial A=0$, the optimal project bonus set by the crowdsourcer under vertical fairness concern is:

$$
A^{NKS*}=\frac{\eta(\lambda+1)^2un^2(n-1)c_e+\lambda un^2}{(\lambda+1)(n-1)} \tag{A4}
$$

It leads the optimal private solution effort and knowledge sharing level under variable project bonus to be

$$
e_i^{NKS*}=\eta^2(\lambda+1)(n-1),s_i^{NKS*}=\frac{(\lambda+1)kc_e-\lambda\beta}{(\lambda+1)nh} \tag{A5}
$$

Substituting back into (A3), we have

$$
\begin{aligned}
&E\left(v^{NKS^*}\right)=\eta\, ln\left(\eta^2(\lambda+1)(n-1)\right)+\frac{\beta\left((\lambda+1)kc_e-\lambda\beta\right)}{(\lambda+1)nh}\\
&\pi_f^{NKS^*}=\eta\, ln\left(\eta^2(\lambda+1)(n-1)\right)+\frac{\beta\left((\lambda+1)kc_e-\lambda\beta\right)}{(\lambda+1)nh}-\frac{un^2\left(\eta(\lambda+1)^2(n-1)c_e+\lambda\right)}{(\lambda+1)(n-1)}\\
&\pi_i^{NKS^*}=\frac{\left(kc_e(\lambda+1)(2n-1)+\lambda\beta\right)\left(kc_e(\lambda+1)-\lambda\beta\right)}{2n^2h(\lambda+1)^2}+\frac{un\left(\eta(\lambda+1)^2(n-1)c_e+\lambda\right)}{(\lambda+1)(n-1)}-\eta^2c_e(\lambda+1)(n-1)
\end{aligned}
\tag{A6}
$$

Proof of Lemma 2

Similar to the NKS model, the decision of the crowdsourcees is solved first. Taking the first partial derivatives of U_i with respect to e_i and s_i respectively, and substituting the symmetry strategy $e_1 = e_2 = ... = e_i = e_i^*$， $s_1 = s_2 = ... = s_i = s_i^*$ obtained from the homogeneity hypothesis, the following equations are obtained:

$$\begin{cases} \dfrac{\partial U_i}{\partial e_i} = \dfrac{(n-1)\eta(\lambda+1)A}{e_i un^2} - (\lambda+1)c_e - \dfrac{\lambda\eta}{e_i} = 0 \\ \dfrac{\partial U_i}{\partial s_i} = (\lambda+1)\left(\dfrac{kc_e}{n} - hs_i + b\theta\right) - \dfrac{\lambda\beta}{n} + \lambda nb\theta = 0 \end{cases} \tag{A7}$$

We get the pooling equilibrium

$$e_i^{KS-} = \frac{\eta\left((\lambda+1)(n-1)A - \lambda un^2\right)}{(\lambda+1)uc_e n^2}, s_i^{KS-}(b) = \frac{(\lambda+1)kc_e - \lambda\beta + ((n+1)\lambda+1)n\theta b}{(\lambda+1)nh} \tag{A8}$$

Obviously e_i^{KS-} and s_i^{KS-} is the optimal private solution effort and knowledge sharing level of the crowdsourcees under KS mode.Then we solve the crowdsourcer's decision. Substituting Formula (A8) back into Formula (9), we get crowdsourcer's benefit expression with respect to *b* as:

$$\begin{aligned} \pi_f(b) = & \eta ln\left(\frac{\eta\left((\lambda+1)(n-1)A - \lambda un^2\right)}{(\lambda+1)uc_e n^2}\right) + \frac{\beta\left((\lambda+1)kc_e - \lambda\beta\right)}{(\lambda+1)nh} \\ & + \frac{\left(((n+2)\lambda+1)\beta - (\lambda+1)kc_e\right)\theta b - ((n+1)\lambda+1)n\theta^2 b^2}{(\lambda+1)h} - A \end{aligned} \tag{A9}$$

It's easy to see that $\pi_f(b)$ is A concave function of *b*. According to $\partial\pi_f(b)/\partial b = 0$, the optimal linear incentive coefficient of knowledge sharing under model KS is obtained. Then we substitute it into Formula (A8) to get optimal knowledge sharing level *s*:

$$b^{KS*} = \frac{((n+2)\lambda+1)\beta - (\lambda+1)kc_e}{2((n+1)\lambda+1)n\theta}, s^{KS*} = \frac{(\lambda+1)kc_e + (n\lambda+1)\beta}{2(\lambda+1)nh} \tag{A10}$$

They lead to

$$A^{KS*} = \frac{un^2\left(\eta(\lambda+1)^2(n-1)c_e + \lambda\right)}{(\lambda+1)(n-1)}, e_i^{KS*} = \eta^2(\lambda+1)(n-1) \tag{A11}$$

Finally, we get the expression of expected project performance and beneficial of both parties under model KS as:

$$
\begin{aligned}
&E\left(v^{KS^*}\right)=\eta ln\left(\eta^2(\lambda+1)(n-1)\right)+\frac{\beta\left((\lambda+1)kc_e+(n\lambda+1)\beta\right)}{2(\lambda+1)nh}\\
&\pi_f^{KS^*}=\eta ln\left(\eta^2(\lambda+1)(n-1)\right)+\frac{\beta\left((\lambda+1)kc_e-\lambda\beta\right)}{(\lambda+1)nh}\\
&-\frac{un^2\left(\eta(\lambda+1)^2(n-1)c_e+\lambda\right)}{(\lambda+1)(n-1)}+\frac{\left(\left((n+2)\lambda+1\right)\beta-(\lambda+1)kc_e\right)^2}{4(\lambda+1)\left((n+1)\lambda+1\right)nh}\\
&\pi_i^{KS^*}=b^{KS*}\theta s_i^{KS*}+kc_e s_i^{KS*}-\frac{hs_i^{KS*2}}{2}+\frac{un\left(\eta(\lambda+1)^2(n-1)c_e+\lambda\right)}{(\lambda+1)(n-1)}-\eta^2c_e(\lambda+1)(n-1)
\end{aligned}
\tag{A12}
$$

Proof of Proposition 1

According to $e_i^{NKS-}>0$ and $s_i^{NKS-}>0$ in Lemma 1, two threshold expressions are obtained. Then calculate the first-order partial derivative of the threshold to λ, we can derive the proposition.

Proof of Proposition 2

The expression of the threshold β is obtained from $b^{KS^*}>0$ in Lemma2, Then calculate the first-order partial derivative of β to λ, we can achieve the proposition.

Proof of Proposition 3

The first partial derivatives of the relevant parameters are obtained by the expression of b^{KS^*} in Lemma 2, we obtain:

$$\frac{\partial b^{KS*}}{\partial \lambda}=\frac{\beta+nkc_e}{2n\left(\left(n+1\right)\lambda+1\right)^2\theta}>0,\frac{\partial b^{KS*}}{\partial \beta}=\frac{\left(\left(n+2\right)\lambda+1\right)}{2n\theta\left(\left(n+1\right)\lambda+1\right)}>0,$$
$$\frac{\partial b^{KS*}}{\partial k}=\frac{-\left(\lambda+1\right)c_e}{2n\left(\left(n+1\right)\lambda+1\right)\theta}<0,\frac{\partial b^{KS*}}{\partial \theta}=-\frac{\left(\left(n+2\right)\lambda+1\right)\beta-\left(\lambda+1\right)kc_e}{2\left(\left(n+1\right)\lambda+1\right)n\theta^2}<0 \tag{A13}$$
$$\frac{\partial b^{KS*}}{\partial n}=-\frac{\left(\left(\left(n+1\right)\lambda+1\right)\left(\left(n+2\right)\lambda+1\right)-n\right)\beta-\left(n^2+\left(\left(n+1\right)\lambda+1\right)\left(\lambda+1\right)\right)kc_e}{n^2\left(\left(n+1\right)\lambda+1\right)^2}$$

So, when $\frac{\beta}{kc_e}>\frac{n^2+\left(\left(n+1\right)\lambda+1\right)\left(\lambda+1\right)}{\left(\left(n+1\right)\lambda+1\right)\left(\left(n+2\right)\lambda+1\right)-n}$, we can get $\frac{\partial b^{KS*}}{\partial n}<0$; vice versa.

Proof of Proposition 4

Comparing the corresponding expressions in Lemma 1 and Lemma 2, we can get that $A^{KS*}=A^{NKS*}$, $e_i^{KS\_}=e_i^{NKS\_}$, $e_i^{KS*}=e_i^{NKS*}$, and have:

$$\frac{\partial A^{KS*}}{\partial \lambda}=\eta un^2\left(n-1\right)c_e+\frac{un^2}{\left(\lambda+1\right)^2\left(n-1\right)}>0,\frac{\partial A^{KS*}}{\partial n}=\eta\left(\lambda+1\right)un^2c_e+\frac{\lambda un\left(n-2\right)}{\left(\lambda+1\right)\left(n-1\right)^2}>0$$
$$\frac{\partial e_i^{KS\_}}{\partial \lambda}=\frac{-1}{\left(\lambda+1\right)^2c_e}<0,\frac{\partial e_i^{KS^*}}{\partial \lambda}=\eta^2\left(n-1\right)>0,\frac{\partial e_i^{KS^*}}{\partial n}=\eta^2\left(\lambda+1\right)>0 \tag{A14}$$

Proof of Proposition 5

Calculating the first order partial derivatives from s_i^{NKS*} and s_i^{KS*} to λ and n respectively, we get:

$$\frac{\partial s_i^{NKS*}}{\partial \lambda}=-\frac{\beta}{nh\left(\lambda+1\right)^2}<0,\frac{\partial s_i^{NKS*}}{\partial n}=-\frac{\left(\lambda+1\right)kc_e-\lambda\beta}{\left(\lambda+1\right)n^2h}<0$$
$$\frac{\partial s_i^{KS*}}{\partial \lambda}=\frac{\left(n-1\right)\beta}{2nh\left(\lambda+1\right)^2}>0,\frac{\partial s_i^{KS*}}{\partial n}=-\frac{\beta+\left(\lambda+1\right)kc_e}{2\left(\lambda+1\right)n^2h}<0,$$
$$s_i^{KS*}-s_i^{NKS*}=\frac{\left(\left(n+2\right)\lambda+1\right)\beta-\left(\lambda+1\right)kc_e}{2\left(\lambda+1\right)nh}>0 \tag{A15}$$
$$\frac{\partial\left(s_i^{KS*}-s_i^{NKS*}\right)}{\partial \lambda}=\frac{\left(n+1\right)\beta}{2nh\left(\lambda+1\right)^2}>0,\frac{\partial\left(s_i^{KS*}-s_i^{NKS*}\right)}{\partial n}=\frac{kc_e-\beta}{2n^2h}$$

Combined with the conditions of Proposition 2, it can be known that when $\beta<kc_e$, $\left(s_i^{KS*}-s_i^{NKS*}\right)$ is positively correlated with n; on the contrary, it is negatively related

to n.

Proof of Proposition 6

Calculating the first order partial derivative from $E\left(v^{NKS*}\right)$ and $E\left(v^{KS*}\right)$ which appear respectively in Equation (13) and (21) to λ, the results are as follows:

$$\begin{aligned}
&\frac{\partial E\left(v^{NKS*}\right)}{\partial \lambda}=\frac{\eta(\lambda+1)nh-\beta^2}{nh(\lambda+1)^2},\frac{\partial E\left(v^{KS*}\right)}{\partial \lambda}=\frac{\eta}{\lambda+1}+\frac{(n-1)\beta^2}{2nh(\lambda+1)^2}>0\\
&E\left(v^{KS*}\right)-E\left(v^{NKS*}\right)=\frac{\left(\left((n+2)\lambda+1\right)\beta-(\lambda+1)kc_e\right)\beta}{2nh(\lambda+1)}>0\\
&\frac{\partial\left(E\left(v^{KS*}\right)-E\left(v^{NKS*}\right)\right)}{\partial \lambda}=\frac{(n+1)\beta^2}{2nh(\lambda+1)^2}>0,\frac{\partial\left(E\left(v^{KS*}\right)-E\left(v^{NKS*}\right)\right)}{\partial n}=-\frac{(\beta-kc_e)\beta}{2n^2h}
\end{aligned}\tag{A16}$$

Then we get $\frac{\eta}{\beta^2}=\frac{1}{hn(\lambda+1)}$ from $\frac{\partial E\left(\overline{v}^{NKS*}\right)}{\partial \lambda}=0$. So when $\frac{\eta}{\beta^2}>\frac{1}{hn(\lambda+1)}$, $\frac{\partial E\left(v^{NKS*}\right)}{\partial \lambda}>0$; when $\frac{\eta}{\beta^2}<\frac{1}{hn(\lambda+1)}$, $\frac{\partial E\left(v^{NKS*}\right)}{\partial \lambda}<0$. Due to $0<\lambda<1$, we have $\frac{1}{2hn}<\frac{1}{hn(\lambda+1)}<\frac{1}{hn}$, Equation (1) is proven. In addition, the sign symbol of $\frac{\partial\left(E\left(v^{KS*}\right)-E\left(v^{NKS*}\right)\right)}{\partial n}$ depends on $(2\lambda+1)\beta-(\lambda+1)kc_e$.

Proof of Proposition 7

The first partial derivative of λ is obtained from the expressions of π_f^{NKS*} and $\pi_f^{KS*}-\pi_f^{NKS*}$ which appear respectively in Equation (13) and (21), the results are as follows:

$$\pi_f^{KS*}-\pi_f^{NKS*}=\frac{\left(\left((n+2)\lambda+1\right)\beta-(\lambda+1)kc_e\right)^2}{4(\lambda+1)\left((n+1)\lambda+1\right)nh}>0$$

$$\frac{\partial\left(\pi_f^{KS*}-\pi_f^{NKS*}\right)}{\partial\lambda}=\frac{\left(\left((n+2)\lambda+1\right)\beta-(\lambda+1)kc_e\right)(n+1)\beta}{\left((n+1)\lambda+1\right)(\lambda+1)^2}+\frac{\left(\left((n+2)\lambda+1\right)\beta-(\lambda+1)kc_e\right)\left(\beta+nkc_e\right)}{(\lambda+1)\left((n+1)\lambda+1\right)^2}>0$$

$$\frac{\partial\left(\pi_f^{KS*}-\pi_f^{NKS*}\right)}{\partial n}=\frac{(\lambda+1)\left((2n+1)\lambda+1\right)kc_e-\left((\lambda+1)\left((n+1)\lambda+1\right)+n\lambda^2\right)\beta}{n^2\left((n+1)\lambda+1\right)^2}*\frac{\left(\left((n+2)\lambda+1\right)\beta-(\lambda+1)kc_e\right)}{4(\lambda+1)h} \qquad \text{(A17)}$$

$$\frac{\partial\pi_f^{NKS*}}{\partial\lambda}=\frac{\eta}{\lambda+1}-\frac{\beta^2}{(\lambda+1)^2nh}-un^2\left(\eta c_e+\frac{1}{(\lambda+1)^2(n-1)}\right)=\frac{\eta(\lambda+1)n(n-1)h\left(1-c_e(\lambda+1)un^2\right)-\left((n-1)\beta^2+un^3h\right)}{(\lambda+1)^2n(n-1)h}$$

Observing the expression of $\frac{\partial\pi_f^{NKS*}}{\partial\lambda}$, we can find that when $1-c_e(\lambda+1)un^2<0$, $\frac{\partial\pi_f^{NKS*}}{\partial\lambda}<0$; otherwise, the sign of $\frac{\partial\pi_f^{NKS*}}{\partial\lambda}$ depends on the sign of $\eta(\lambda+1)n(n-1)h\left(1-c_e(\lambda+1)un^2\right)-\left((n-1)\beta^2+un^3h\right)$. Because $\frac{\partial\pi_f^{KS*}}{\partial\lambda}=\frac{\partial\pi_f^{NKS*}}{\partial\lambda}+\frac{\partial\left(\pi_f^{KS*}-\pi_f^{NKS*}\right)}{\partial\lambda}$, when $\frac{\partial\pi_f^{NKS*}}{\partial\lambda}>0$, $\frac{\partial\pi_f^{KS*}}{\partial\lambda}>0$ must be established, otherwise, the sign of $\frac{\partial\pi_f^{KS*}}{\partial\lambda}$ cannot be judged.

Impact of crowdsourcee's vertical fairness concern on the crowdsourcing knowledge sharing behavior and its incentive mechanism

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