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Abstract
In the knowledge-based view of the firm, organizational knowledge and expertise are recognized as primary drivers of continuous innovation and competitive advantage. However, as an intangible resource knowledge resides within individuals who personally value their skills and therefore have an implicit incentive to keep knowledge private. Consequently, it is necessary for organizations to provide adequate rewards to control the diffusion and utilization of knowledge among their employees. The purpose of this paper is to develop and analyze a reward structure that motivates agents to generate additional knowledge and subsequently share it with co-workers. In this context, creation and sharing are considered costly actions that, in turn, decrease the cost of providing an output-oriented effort. The optimal incentive structure is derived to balance the explicit incentives of monetary rewards and the implicit benefits associated with a higher level of private knowledge. The model suggests that organizations need to choose whether they want to emphasize either the creation or dissemination of knowledge. The optimal effort level for sharing knowledge depends not only on an agent's personal incentive, but more importantly on the marginal productivity and the incentive of other agents to efficiently apply the shared knowledge. However, stronger incentives to generate knowledge have a detrimental effect on each agent's willingness to share and vice versa. The findings in this paper should help to further understand organizational learning and the transfer of developed knowledge. Furthermore, it provides insights into the trade-off between the creation and sharing of knowledge, which should aid managers to better design incentive contracts for employees to focus their attention on the desired task.

Keywords: knowledge sharing, principal-agent, learning, knowledge management, co-operation

"Every afternoon our corporate knowledge walks out the door and I hope to God they'll be back tomorrow"

——Miller (1998), Keynote Address

1 Introduction

In the past three decades the creation, utilization and especially the diffusion of knowledge within organizations has drawn the attention of both researchers and companies alike (Hislop, 2010). In the knowledge-based view of the firm, organizational knowledge and expertise are even considered as primary drivers of continuous innovation and competitive advantage (e.g. Argote and Ingram (2000), Davenport and Prusak (1998), Nonaka et al. (2000)). However, knowledge that is kept private only benefits single employees or departments, whereas units that work together can leverage benefits of mutual creation and sharing. Therefore, it is in the interest of organizations to control the diffusion and utilization of knowledge among their employees. In general, knowledge transfer can be defined as the process in which one unit of a firm is affected by the expertise of others (Singley and Anderson, 1989) and occurs through different mechanisms including formal and informal exchanges among co-workers, organizational databases, communities of practice or the transfer of technologies (Davenport and Prusak, 1998).

Implementing knowledge sharing and knowledge management programs potentially offers multiple benefits towards a company. It builds up repositories and prevents the loss of knowledge due to employee turnovers or transfers. It fosters the diffusion of innovations throughout the organization so that the company as whole can benefit from the findings of single workers or divisions. It further helps to avoid redundancies from repeating the same work processes or researching the same information. Gathering heterogeneous knowledge allows companies to leverage synergy effects by combining different streams of expertise. In general it is assumed that effective knowledge management lowers the cost of production. Recognizing the potential benefits of managing knowledge exchange, many companies have already successfully implemented knowledge management systems or programs. For example Siemens (Davenport and Probst, 2002), Hewlett and Packard (Davenport and Völpel, 2001), Toyota (Dyer and Nobeoka, 2000) and all of the Big Four (Vera-Munoz et al., 2006) report significant performance increases due to the diffusion of employee knowledge within the organization. Moreover, in a study conducted by KPMG 81 percent of included European and American companies either already had or were currently working on implementing a knowledge management program. However, of the companies that implemented knowledge management into their organizational routine 36 percent reported that benefits failed to meet the expectations (KPMG, 2000).

In contrast to more typical factors of production, knowledge resides within individuals who dynamically generate and implement it to fulfill their tasks. Knowledge therefore can best be described as an intangible asset. The process of knowledge sharing itself is unobservable and unverifiable, thus there are no measures that can effectively be utilized for contracting purposes. Moreover, fostering knowledge sharing might not always be in the best interest of the principal. Companies need to consider possible trade-offs between the creation, diffusion and application of knowledge. Baum and Ingram (1998) argue that knowledge transfer can have negative effects, if the transferred knowledge is too complex and cannot be adopted by the recipients. Additionally, sharing is costly to agents in two ways: First, it requires time and effort to structure knowledge in order to render it transferable. Second, employees personally value their knowledge and skills, thus are reluctant to freely share their information (Blair, 2002). Workers might even consider colleagues as competitors within the firm or on the labor market and thus feel that they jeopardize employment or promotion opportunities by giving up power (Davenport and Probst, 2002). As a result, appropriate reward structures are necessary to foster knowledge sharing among co-workers.

Even though, knowledge sharing has received an increased interest from researchers in the past, insights about the economic effects of rewards are still limited. The purpose of this paper is to address this research gap by developing and analyzing a reward structure that motivates agents to both generate knowledge to decrease their individual effort costs of production and subsequently to share this knowledge to indirectly influence the performance of co-workers. Furthermore, the necessary conditions for when and how much knowledge sharing is preferred by the principal are analyzed. Through the analysis of the principal-agent model and the resulting equilibrium surpluses, the paper is able to show that mutual knowledge creation and sharing among employees is in optimum desired by the principal. However, the principal cannot necessarily control the allocation of an employee's time and effort among the tasks. It is not sufficient to motivate one agent to share knowledge as it alone adds no value to the firms output, but instead individual and sharing oriented incentives have to be in place to both motivate the diffusion and application of knowledge. Furthermore, when agents vary in their skill level, especially in their marginal productivity, the less skilled worker only witnesses a minor increase in his output upon receiving shared knowledge. In this situation, it is optimal for the less productive employee to assume the role of a support and to focus on generating and supplying knowledge towards the more productive worker who can better integrate knowledge into his already superior routines to maximize the effect on performance.

The remainder of this paper is structured as follows: The next section provides a short overview of the related literature. Second, a principal-agent model is developed to explore the multi-task moral hazard problem in which a single agent can generate additional knowledge to decrease his disutility of providing an output related effort. Furthermore, the optimal incentive structure is derived to balance the explicit incentives of monetary rewards and the implicit benefits associated with a higher level of private knowledge. Third, the presented model is extended to incorporate an additional agent in order to analyze the strategic interaction of creating and sharing knowledge. In an extension to the multi-agent setting, the principal faces the decision of investing into knowledge management technology, which in turn lowers the agents' effort costs of sharing knowledge and provides a signal that can be utilized for contracting. Finally, the findings and implications are discussed and possible limitations as well as avenues for future research are addressed.

2 Related Literature

As highlighted in the introduction, a vast amount of articles on the topic of knowledge management is available from multiple research streams. However, in this section only contributions from literature related to theoretical approaches that model the exchange of information among co-workers are highlighted.

In a game theoretical approach, Loebecke et al. (1999) model an agent's decision to share knowledge with a co-worker. In the proposed game, two agents have the choice of either sharing or hoarding their knowledge. When both agents decide to share their knowledge they gain a synergetic value from mutual knowledge sharing but lose the monopolistic value of keeping their knowledge private. The situation in which both agents cooperate with each other maximizes the social surplus, however each agent has the incentive to deviate from this strategy and instead keep their knowledge private. In the game, the agents are not able to convincingly commit to sharing knowledge with each other and the game can thus be described as a prisoner's dilemma. The resulting Nash-equilibrium is a situation in which nobody shares his information, even though both agents would be better off if they combined their knowledge. Consequently, due to costs of sharing and the loss of private benefits, the strategy to hoard knowledge is dominant. The approach of the game theoretical model provides insights into the topic of knowledge sharing or cooperation among agents in general, but does not offer a solution to the game.

As knowledge sharing among co-workers includes the interaction of multiple agents the principal-agent models of Itoh (1991), as well as, Auriol et al. (2002) are related to the structuring of this paper. The models each describe a multi-task setting in which agents can provide an individual effort to enhance their own output and a "helping" effort to directly increase the performance measure of other workers. The efforts, therefore, can be considered as substitutes. However, this approach differs from the setting considered in this paper. Knowledge itself offers no direct value towards a firm's output and only lowers the disutility of providing an output-oriented effort. The sharing effort of one worker and the productive effort of the other employee thus take the form of complements rather than substitutes.

Kvaløy and Schöttner (2015) analyze the optimization problem of a principal that hires two employees with separate tasks. One agent is tasked with producing an output, whereas the second agent provides a motivational support for the former. Motivation is assumed enjoyable to the receiving agent and has a reducing effect on his effort costs. The structuring of the cost function of the agent that receives the support is similar to the one in this paper as shared knowledge is also assumed to reduce an agent's effort cost. However, in their modeling the agents assume separate roles within the organization and as such, the analysis of the interaction among employees is not emphasized. They instead focus their attention on the trade-off between monetary and motivational incentives.

Lee and Ahn (2007) provide a principal-agent model for knowledge sharing and also model the loss of private benefits when doing so. However, they assume that measures for knowledge sharing are in place and that it adds direct value to the firm. They further construct the model in a manner that suggests that more experienced workers should be induced to share more, because they lose less utility of private knowledge. They also argue that knowledge from experienced workers contributes more towards firm performance.

Siemsen et al. (2007) shortly analyze the impact of knowledge sharing on the effort cost of the receiving agent and demonstrate that multiple types of incentives are necessary for knowledge sharing to have any effect on performance. The holder of knowledge must be provided with an incentive to share his valuable information and the recipient must be provided with an incentive to apply the shared knowledge. However, the model itself is not further investigated.

Nan (2008) also develops a principal-agent model that focuses on incentive designs for different types of knowledge, which vary in their visibility and verifiability. In this model knowledge can either be explicit, thus easily transferable with low intangibility such as data or documents, or tacit with high intangibility such as expertise or experience. The developed model derives the optimal incentive scheme for knowledge sharing in regards to the tangibility of shared knowledge. However, sharing is the only considered effort and no further trade-offs between the creation or application of knowledge are considered.

Finally, Sundaresan and Zhang (2004) propose a principal-agent model in which only the more knowledgeable employee can share his knowledge, whereas the less knowledgeable worker can only absorb the shared knowledge. Furthermore, they model an IT system that supports the agents knowledge collecting and donating activities by reducing the effort costs of agents. In the model, a combined team output is considered and the sharing and absorption efforts are, to some extent, considered to be observable.

3 The Model

The principal-agent model is developed in three distinct settings. First, only a single risk-averse agent who has the opportunity to generate additional knowledge before performing a task related effort is considered. In the second setting, multiple agents further have the option to exchange their generated knowledge to indirectly affect the productive output of each other. In the third setting, the principal also has to decide whether she wants to invest in a knowledge management system to i) decrease the cost of knowledge sharing and ii) to provide a signal to monitor the amount of knowledge shared. In order to keep the structure of the model simple, the well-known LEN-framework is utilized with linear bonus functions, exponential utility functions and normally distributed noise terms.[1]

3.1 Single agent with learning

In the first setting, the multi-task model consists of a risk neutral principal and a risk averse employee who is tasked to provide a knowledge intensive effort. The employee's output is given as follows:

$$y = e \cdot b + \varepsilon$$

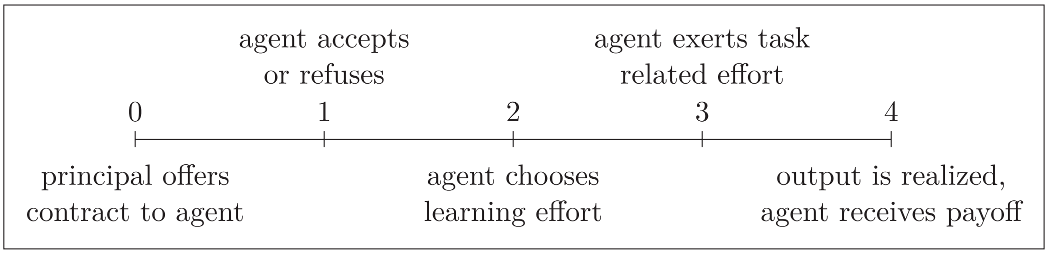
Where $b > 0$ denotes the employee's commonly known contribution of effort towards the task related output y. The noise of the performance measure is represented by ε and is normally distributed with mean zero and variance σ^2. Before the employee engages in effort (e) to fulfill the task, he has the option of exerting a learning effort denoted as kc (knowledge creation) to gather further information about the task. This effort can be understood as improving existing production/work processes, streamlining routines to avoid redundancies or simply spending time and effort to increase the personal skill level. Doing so will lower the cost of providing the output oriented effort (e). This effect is represented as a reduction in the effort costs of the employee and has an indirect influence on his output. The cost of efforts e and kc are denoted as:

$$C(e, kc) = \frac{1}{2}\left(\frac{c_e \cdot e^2}{kc} + \frac{c_{kc} \cdot kc^2}{p \cdot k}\right)$$

[1] See for example Holmstrom and Milgrom (1991) for a detailed description of a linear multi-task principal-agent model.

The additive components of the cost function imply that there is no crowding-out effect between the two efforts. The parameters $c_e \geq 1$ and $c_{kc} \geq 1$ represent scalars for the effort costs and knowledge creation costs respectively. Furthermore, the agent receives a private benefit ($p \geq 1$) by having a greater understanding and knowledge level due to learning, which can be understood as a feeling of superiority, power or as competitive advantage on the job market due to privately owning specific knowledge about certain production processes (Loebecke et al., 1999). An increase in the private benefit lowers the agent's marginal effort costs of learning additional knowledge.[2] For example, a worker who anticipates that his current contract might end soon, will be more willing to spend further effort into increasing his skills compared to an employee whose position is secure and who is unlikely to be competing in the job market in the near future. Finally, the parameter $k \geq 1$ denotes the cognitive capacity of the employee. This represents the general ability to absorb and apply knowledge and in turn decreases the cost of the knowledge creation effort kc. The assumption that additional knowledge and information have a positive influence on effort costs is in line with current literature (e.g. Davenport and Prusak (1998), Baum and Ingram (1998), Argote and Ingram (2000)).[3] In summary, the sequence of events is displayed in the following figure:

Figure 1: *Single agent with learning*



The agent's salary function s(y) is a linear function of the output y with incentive coefficient α ($0 \leq \alpha \leq 1$) and ζ as fixed remuneration:

$$s(y) = \zeta + \alpha \cdot y$$

The agent is assumed to be risk averse with r as the Arrow-Pratt measure of constant absolute risk-aversion. Hence, the preferences of the employee can be described by his utility function given as:

$$U(s(y), e, kc) = -\exp(-r(s(y) - C(e, kc)))$$

Following the structure of the LEN-framework (Spremann, 1987), the agent's certainty

[2] It might seem more intuitive to model the benefit of keeping knowledge private as a direct increase of the agent's marginal utility, for example as an additive component in the form of p(kc). However, this greatly increases the complexity of the results and the optimal bonus coefficients would no longer be interpretable. Therefore, the agent's benefit of additional knowledge is modeled to decrease his disutility of the knowledge creation effort.

[3] A version of the model, where the knowledge creation effort has a more direct impact on the agents' output is considered to take the form of $y = (1 + kc) \cdot b \cdot e$. This modeling provides similar results for the optimal effort levels, however, provides no interior solution for the optimal bonus coefficients.

equivalent can then be expressed as:

$$CE = E[s(y)] - C(e,\ kc) - \frac{r}{2} \cdot VAR[s(y)]$$

3.1.1 Benchmark solution

As a benchmark for the optimization problem, the first-best solution is considered, where both the task-related effort and the knowledge creation effort of the agent are observable and verifiable by the principal; whose optimization problem can then be described by:

$$\max_{e,\, kc} \pi = E[y - s(y)]$$

subject to:

$$E[s(y)] - C(e,\ kc) \geq 0 \qquad \text{(PC)}$$

In this setting, the principal can set a fixed remuneration for the agent and no effort incentives are necessary, therefore the agent bears no risk. The optimal fixed compensation must only compensate the agent's disutility of effort since his reservation utility, for the purpose of this paper, is set to zero. Constructing the total surplus and solving for the optimal effort levels provides the following solution:

Lemma 1. *The first-best effort levels are given by:*

$$e^{FB} = \frac{b \cdot kc^{FB}}{c_e}, \quad kc^{FB} = \left(\frac{k \cdot p \cdot c_e \cdot (e^{FB})^2}{2 \cdot c_{kc}} \right)^{\frac{1}{3}}$$

after substitution:

$$e^{FB} = \frac{b^3 \cdot k \cdot p}{2 \cdot c_e^2 \cdot c_{kc}}, \quad kc^{FB} = \frac{b^2 \cdot k \cdot p}{2 \cdot c_e \cdot c_{kc}}$$

resulting equilibrium surplus equals:

$$\pi^{FB} = \frac{b^4 \cdot k \cdot p}{8 \cdot c_e^2 \cdot c_{kc}}$$

It is apparent that the equilibrium surplus increases with the marginal productivity of effort (b), the agent's cognitive capacity (k) and the private benefit of knowledge (p), but decreases with the effort costs (c_e, c_{kc}). Furthermore, both effort levels increase in each other, thus take the form of complements.

3.1.2 Under moral hazard

Under the assumption that both effort levels are unobservable for the principal and that only the signal y is available for contracting, the principal's optimization problem extends to:

$$\max_{\alpha} E[y - s(y)]$$

subject to:

$$\mathrm{CE} \geq 0 \qquad \text{(PC)}$$

$$\mathrm{e},\ \mathrm{kc} = \operatorname{argmax} \mathrm{CE} \qquad \text{(IC)}$$

The incentive constraint (IC) ensures that the agent chooses the optimal effort levels dependent upon his certainty equivalent and the incentive coefficient α, whereas the participation constraint (PC) ensures that the agent accepts the contract. To solve the optimization problem the agent first chooses his optimal effort levels given his certainty equivalent. This result is then substituted into the optimization problem of the principal, which provides the following solutions:

Lemma 2. *The second-best effort levels are given by:*

$$e^{SB} = \frac{\alpha \cdot b \cdot kc^{SB}}{c_e}, \quad kc^{SB} = \left(\frac{k \cdot p \cdot c_e \cdot (e^{SB})^2}{2 \cdot c_{kc}}\right)^{\frac{1}{3}}$$

and after substitution:

$$e^{SB} = \frac{\alpha^3 \cdot b^3 \cdot k \cdot p}{2 \cdot c_e^2 \cdot c_{kc}}, \quad kc^{SB} = \frac{\alpha^2 \cdot b^2 \cdot k \cdot p}{2 \cdot c_e \cdot c_{kc}}$$

resulting equilibrium surplus equals:

$$\pi^{SB} = \frac{\alpha^3 \cdot b^4 \cdot k \cdot p}{2 \cdot c_e^2 \cdot c_{kc}} - \frac{3 \cdot \alpha^4 \cdot b^4 \cdot k \cdot p}{8 \cdot c_e^2 \cdot c_{kc}} - \frac{r \cdot \alpha^2 \cdot \sigma^2}{2}$$

From lemma 2 it is apparent that it is optimal for the agent to invest in the knowledge creation effort when his incentives to provide a productive effort increase. However, the optimal knowledge creation effort under second-best reacts only weakly to the monetary incentive provided by the coefficient α, but in fact is much stronger influenced by the private benefit the agent experiences due a higher level of knowledge. The knowledge creation effort is not directly affected by the bonus coefficient, but instead increases when the task-related effort increases. Hence, the principal is not able to set incentives for knowledge creation directly and can only control the motivation for the productive effort. This result is similar to findings of Feltham and Xie (1994) such that the principal can only influence to total intensity of effort but not the proportional division among multiple tasks as no separate performance measure for the knowledge intensive effort is available for contracting. However, she could influence the intrinsic benefits the agent enjoys from knowledge by, for example, providing the agent with additional autonomy over findings or instituting employee recognition programs. Google's "20% time policy" is often mentioned as a prime example for companies which offer employees additional time to work on their own projects and sharpen their skills (Laux, 2017). Hence:

Proposition 1. *The principal can set the bonus coefficient* α *to provide stronger or weaker incentives to provide both the productive and the knowledge creation effort, but cannot set the proportional allocation among tasks.*

Furthermore, it is interesting to note that it seems intuitive to assume that the agent would increase his efforts to generate additional knowledge to substitute for the cost of effort (c_e). However, this effect is not strong enough to compensate for the absolute reduction in the task-related effort when the costs increase. Knowledge itself adds no direct value to the performance measure and if the output related effort decreases, the optimal level of knowledge creation also decreases. Ultimately, the latter effect outweighs the substitution effect and the agent generates less knowledge as the cost of the task-related effort increases.[4] Utilizing the equilibrium surplus to solve for the bonus coefficient α results in:

Proposition 2. *The optimal incentive coefficient* α *is denoted as:*

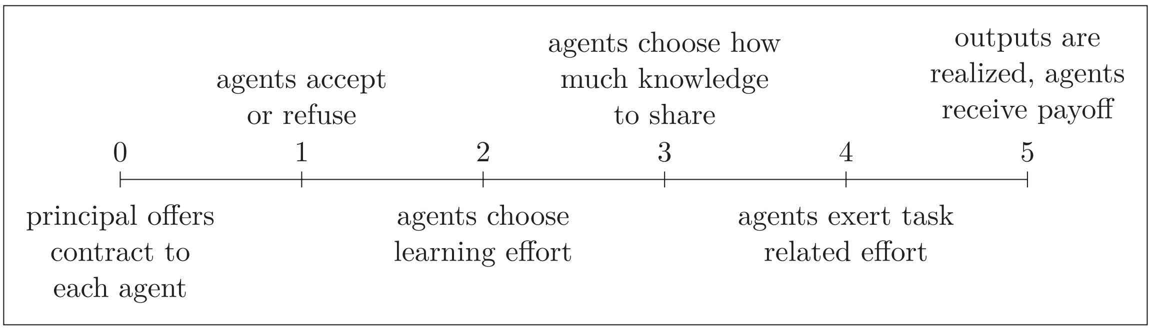
$$\alpha = \frac{1}{2} + \frac{\sqrt{9 \cdot b^4 \cdot k^2 \cdot p^2 - 24 \cdot c_e^2 \cdot c_{kc} \cdot k \cdot p \cdot r \cdot \sigma^2}}{6 \cdot b^2 \cdot k \cdot p}$$

Proposition 2 shows that the optimal bonus coefficient increases in the agent's marginal productivity of task related effort (b), his cognitive capacity (k) and private benefit of knowledge (p). However, reduces in the effort cost of the output oriented effort (c_e), the effort cost of creating knowledge (c_{kc}), the variance of the output (σ^2) and the agent's risk aversion (r).

3.2 Multiple agents with learning and sharing

In this extension of the first setting, it is now assumed that the organization employs a second agent. Both agents, indexed by $i \in I = 1, 2$, are tasked with performing an output orientated work effort and can, as in the single agent setting, exert a learning effort to "sharpen their skills" before beginning their work. However, in this new setting the agents can also strategically share their knowledge (ks_i) with one another to effectively lower each other's cost of providing the productive effort. Both employees work on their own projects, thus their performance is separable and measured by their individual output levels y_i. The extended sequence of events is shown in the following figure:

Figure 2: *Multiple agents with learning and sharing*



Sharing is costly to the agents in two ways: agents need to spend time and effort to make their individual knowledge transferable, this for example represents the cost of organizing information or documenting procedures. Furthermore, the sharing agent values his private knowledge, which provides him with an implicit incentive to instead hoard it. To express the disutility from sharing private knowledge the effort cost for sharing increases in p_i,

[4] To keep the model traceable in the multi-agent setting all effort cost factors are set to equal 1 for the remainder of the paper, such that: $c_{e_i} = c_{kc_i} = c_{ks_i} = 1$.

whereas the costs for generating knowledge still decrease in it. Hence, the total cost of efforts for each agent expands to:

$$C_i(e_i, kc_i, ks_i) = \frac{1}{2} \cdot \left(\frac{e_i^2}{kc_i + ks_j} + \frac{kc_i^2}{k_i \cdot p_i} + \frac{ks_i^2 \cdot p_i}{k_i \cdot k_j} \right)$$
$$\text{where } j \in I \setminus i$$

To indicate that it requires less effort to learn from others than privately generating knowledge, the effort costs for sharing knowledge decrease in the cognitive capacity (k_i) of both agents combined. Intuitively one could say that a sharing agent with a high cognitive capacity is better able to structure his knowledge so that the recipient needs to spend less effort deciphering the information. Given the earlier payoff structure of the agents, it should be obvious, that the individual incentive coefficient (α_i) alone is not sufficient to induce the agents to share their knowledge with each other, so that $\frac{\partial ks_i}{\partial \alpha_i} = 0$. Hence, it is necessary to implement a collective incentive coefficient β_i such that the wage function of agents extends to:

$$s_i(y_i, y_j) = \alpha_i \cdot y_i + \beta_i \cdot y_j + \zeta_i$$

It is assumed that each agent's individual output y_i is observable and verifiable and that there is no combined team output. By structuring each agent's wage function so that payoff also depends on the performance of the other agent contingent on the bonus coefficient β_i, the principal can induce teamwork among the agents. This form of wage scheme is normally referred to as relative performance evaluation (RPE). Holmstrom (1982) and Mookherjee (1984) show that this structure can be utilized to insure the agents against risk by filtering out common shocks. This is however only possible if the individual outputs are correlated. In such a setting the collective incentive coefficient normally receives a negative sign to even out the scale and to isolate the common shock (Gibbons and Murphy, 1990). However, Itoh (1991) shows that utilizing RPE is detrimental when trying to induce cooperation among agents. Here, both outputs are assumed to be stochastically independent and that there are no insurance benefits by applying RPE. The variance of the agents' salary can be described as:

$$VAR(s_i) = \alpha_i^2 \cdot \sigma_i^2 + \beta_i^2 \cdot \sigma_j^2$$

The agents can, however, actively influence the performance of co-workers by sharing valuable knowledge. When one employee supports the other, the effort costs of the second agent decrease and his equilibrium output, in turn, will increase, which enhances the wage of the first agent. Under this premise it is plausible to assume that all incentive coefficients are greater than or at least equal to zero in order to induce the agents to cooperate. Besides the effort costs for sharing the agents' problem arises through the trade-off between the implicit benefit of keeping knowledge private and the monetary incentive they receive when supporting other agents.

3.2.1 Benchmark solution

Agents can only share knowledge that they previously have generated themselves, such that $ks_i \leq kc_i$ (sharing constraint). This adds an additional constraint to the principal's optimization problem. When constructing the Lagrangian of the optimization problem it is unclear whether this sharing restriction is binding, thus there are multiple solutions to this problem, which can be expressed as:

$$\max_{e_i,\, kc_i,\, ks_i} \pi = \sum_{i=1}^{n} E[y_i - s_i(y_i,\ y_j)]$$

subject to:

$$E[s_i(y_i,\ y_j)] - C_i(e_i,\ kc_i,\ ks_i) \geq 0 \qquad \text{(PC)}$$

$$ks_i \leq kc_i \qquad \text{(SC)}$$

$$\forall\ i = 1, 2$$

Solving the Lagrangian of the problem provides the following results:[5]

Lemma 3. *The first-best effort levels are given by:*

$$e_i^{FB} = b_i \cdot (kc_i^{FB} + ks_j^{FB})$$

$$kc_i^{FB} = \max\left\{\frac{b_i^2 \cdot k_i \cdot p_i}{2};\ \frac{k_i \cdot k_j \cdot p_i \cdot \left(b_i^2 + b_j^2\right)}{2 \cdot \left(k_j + p_i^2\right)}\right\}$$

$$ks_i^{FB} = \max\left\{\frac{b_j^2 \cdot k_i \cdot k_j}{2 \cdot p_i};\ \frac{k_i \cdot k_j \cdot p_i \cdot \left(b_i^2 + b_j^2\right)}{2 \cdot \left(k_j + p_i^2\right)}\right\}$$

and after substitution:

$$e_i^{FB}(1,2,3,4) = \quad (1) = b_i \cdot \left(\frac{b_i^2 \cdot k_i \cdot p_i}{2} + \frac{b_i^2 \cdot k_i \cdot k_j}{2 \cdot p_j}\right)$$

$$(2) = b_i \cdot \left(\frac{b_i^2 \cdot k_i \cdot p_i}{2} + \frac{k_i \cdot k_j \cdot p_j \cdot \left(b_i^2 + b_j^2\right)}{2 \cdot \left(k_i + p_j^2\right)}\right)$$

$$(3) = b_i \cdot \left(\frac{k_i \cdot k_j \cdot p_i \cdot \left(b_i^2 + b_j^2\right)}{2 \cdot \left(k_j + p_i^2\right)} + \frac{b_i^2 \cdot k_i \cdot k_j}{2 \cdot p_j}\right)$$

$$(4) = b_i \cdot \left(\frac{k_i \cdot k_j \cdot p_i \cdot \left(b_i^2 + b_j^2\right)}{2 \cdot \left(k_j + p_i^2\right)} + \frac{k_i \cdot k_j \cdot p_j \cdot \left(b_i^2 + b_j^2\right)}{2 \cdot \left(k_i + p_j^2\right)}\right)$$

An agents knowledge creation effort can either be low= $\frac{b_i^2 \cdot k_i \cdot p_i}{2}$ or high= $\frac{k_i \cdot k_j \cdot p_i \cdot \left(b_i^2 + b_j^2\right)}{2 \cdot \left(k_j + p_i^2\right)}$. The low level of effort equals the first-best effort level of knowledge creation in the single agent setting and denotes an equilibrium where an agent is not motivated to increase his knowledge creation effort (kc_i) to support the other agent. This solution is referred to

[5] The optimization problem of the principal can be described as: $\mathcal{L} = b_i e_i + b_j e_j - C_i(e_i, kc_i, ks_i) - C_j(e_j, kc_j, ks_j) - \lambda_i(kc_i - ks_i) - \lambda_j(kc_j - ks_j)$ with λ_i and λ_j as the Lagrange multipliers for the sharing constraints.

as the individual equilibrium level of knowledge creation. If a worker exerts the low level of knowledge creation effort, he will only share part of his knowledge with $ks_i < \frac{b_i^2 \cdot k_i \cdot p_i}{2}$. However, if an agent is motivated to exert the high level of creation effort, he will always share his knowledge completely and $ks_i = kc_i$. As both agents can engage in the high or low level of knowledge creation and sharing there are four solutions of the optimal productive effort denoted as (1, 2, 3, 4). In (1) both agents create knowledge according to their individual equilibrium. In (2) and (3) one of the agents will create and share above his individual equilibrium, whereas in (4) both agents will create and share above their individual solution. The threshold for when an agent should switch strategies can be derived from the levels of creation and sharing. An agent will provide the low level of creative effort and sharing until $ks_i = \frac{b_j^2 \cdot k_i \cdot k_j}{2 \cdot p_i} > kc_i = \frac{b_i^2 \cdot k_i \cdot p_i}{2}$, which can be rearranged to provide:

Proposition 3. *Given the threshold:*

$$\frac{b_j^2}{b_i^2} > \frac{p_i^2}{k_j}$$

it is optimal for agent i to generate and share knowledge above his individual equilibrium.

Intuitively, $\frac{b_j^2}{b_i^2}$ represents the ratio of the agents' marginal productivities, whereas the right hand side represents the additional costs for sharing knowledge. In other words, if the increase in the recipient's output upon receiving an additional unit of knowledge is greater than the sender's costs for sharing ($p_i^2 b_i^2$), then the less productive agent (in this setting agent i) will focus his attention towards the creation and provision of additional knowledge to take advantage of the high productivity of the other agent. In this case agent i should choose an effort level for knowledge creation above his individual optimum. By doing so the less efficient worker can exploit the productivity of the other worker. This is in contrast to earlier findings in the literature. Sundaresan and Zhang (2004) and Lee and Ahn (2007) report that it is in the interest of the principal that only the more knowledgeable and skilled employee should share his knowledge to increase the productivity of the less skilled worker and to even out the performance differences among them. However, here the less productive worker assumes the role of a supporting agent and focuses on creating and providing knowledge for the more productive worker. Through this teamwork arrangement the high productivity of worker j is leveraged as much as possible and agent i's focus lies on further decreasing worker j's cost of effort. When the threshold is not reached and the agents are similar in their marginal productivity of effort, they work well as a team and will both create and share knowledge at their individual optimum. From lemma 3 it follows that the resulting equilibrium surpluses then are:

Lemma 4. *The first-best equilibrium surpluses are:*[6]

$$(1) \quad \pi^{FB} = \frac{b_i^4 k_i p_i^2 p_j + b_j^4 k_j p_i p_j^2 + b_i^4 k_i k_j p_i + b_j^4 k_i k_j p_j}{8 p_i p_j}$$

[6] See the appendix for a comparison of the individual equilibria.

$$(2) \quad \pi^{FB} = \frac{k_i(b_i^4 p_i^2 p_j^2 + b_i^4 k_i p_i^2 + b_i^4 k_j p_i p_j + 2b_i^2 b_j^2 k_j p_i p_j + b_j^4 k_j p_i p_j + b_j^4 k_j p_j^2 + b_j^4 k_i k_j)}{8p_i(k_i + p_j^2)}$$

$$(3) \quad \pi^{FB} = \frac{k_j(b_j^4 p_j^2 p_i^2 + b_j^4 k_j p_j^2 + b_j^4 k_i p_j p_i + 2b_j^2 b_i^2 k_i p_j p_i + b_i^4 k_i p_j p_i + b_i^4 k_i p_i^2 + b_i^4 k_j k_i)}{8p_j(k_j + p_i^2)}$$

$$(4) \quad \pi^{FB} = \frac{k_i k_j (b_i^2 + b_j^2)^2 (p_i^2 p_j + p_i p_j^2 + k_i p_i + k_j p_j)}{8(p_i^2 + k_j)(p_j^2 + k_i)}$$

A comparison of the results with and without knowledge sharing further provides:

Corollary 1. *It is optimal for the principal to induce knowledge sharing among agents.*

If, for example, both agents are equal, the value added of knowledge sharing compared to no exchange among agents equals $\Delta\pi = b_i^4 k_i k_j p_i + b_j^4 k_i k_j p_j$, which is strictly positive.[7] Hence, the equilibrium surplus with knowledge sharing is strictly greater than without and it is in the first-best setting always optimal for the principal if agents cooperate. Sharing or exchanging knowledge combines the expertise and cognitive capacity of agents (represented by k), thus sharing is assumed to be less costly then individually creating a high amount of knowledge. Agents that work together can leverage benefits of mutual knowledge creation and sharing to generate a larger stock of knowledge than individual agents. This finding further highlights and provides methodological proof of predictions from the behavioral science and empirical findings reported by Argote and Ingram (2000), Baum and Ingram (1998).

3.2.2 Under moral hazard

Under moral hazard, the effort levels of the agents are again no longer observable or verifiable by the principal. However, it is assumed that the agents can anticipate each other's willingness to adopt shared knowledge. This is intuitive as most knowledge sharing is done with direct contact between the agents. It is often also assumed that a majority of knowledge exchange at the workplace takes place during off-hours or in situations in which there is some slack, for example during downtimes, lunch, social events or the so called water-cooler talks (Davenport and Prusak, 1998). Therefore, knowledge exchange does not negatively affect the effort exerted into their individual tasks (crowding-out) and the sharing agent can directly observe the recipients effort to apply the new information. For the remainder of this section the focus lies on the constellation of agents that are similar in their marginal productivities, so that no agent supposedly takes on the role of support for the higher skilled employee. Furthermore, this limits the possible solutions and isolates the incentive provided by the bonus coefficients.[8] The principal's optimization problem under moral hazard can be described by:

$$\max_{\alpha_i, \beta_i} \pi = \sum_{i=1}^{n} E[(1 - \alpha_i - \beta_j) \cdot y_i]$$

subject to:

[7] See the appendix for a proof of corollary 1.

[8] An overview of all possible solutions is available from the author upon request.

$$CE_i = \alpha_i \cdot y_i + \beta_i \cdot y_j - C_i(e_i, kc_i, ks_i) - \frac{r_i}{2} \cdot VAR(s_i) \geq 0 \tag{PC}$$

$$e_i, kc_i, ks_i = \operatorname{argmax} CE_i \tag{IC}$$

$$ks_i \leq kc_i \tag{SC}$$

$$\forall\, i = 1, 2$$

Through the sharing constraint (SC) the principal is further able to influence the agents' willingness to generate additional knowledge by setting a high bonus coefficient dependent upon the performance of the other agent. With a strong incentive to share knowledge the agent respectively has an implicit incentive to further generate additional knowledge. Solving the Lagrangian of the optimization problem provides the following results:

Lemma 5. *Under asymmetric information, the optimal effort levels are given by:*

$$e_i^{SB} = \alpha_i b_i \cdot (kc_i^{SB} + ks_j^{SB})$$

$$kc_i^{SB} = \max\left\{\frac{b_i^2 k_i p_i (\alpha_i + \beta_j)^2}{2};\ \frac{b_i^2 b_j^2 k_i k_j p_i (\alpha_i + \beta_j)^2 (\alpha_j + \beta_i)^2}{2(p_i^2 + k_j)}\right\}$$

$$ks_i^{SB} = \max\left\{\frac{\alpha_j \beta_i b_j^2 k_i k_j}{p_i};\ \frac{b_i^2 b_j^2 k_i k_j p_i (\alpha_i + \beta_j)^2 (\alpha_j + \beta_i)^2}{2(p_i^2 + k_j)}\right\}$$

and after substitution:

$$\begin{aligned}
e_i(1,2,3,4) = \quad & (1) = \alpha_i b_i \left(\frac{b_i^2 k_i p_i (\alpha_i + \beta_j)^2}{2} + \frac{\alpha_i \beta_j b_i^2 k_i k_j}{p_j}\right) \\
& (2) = \alpha_i b_i \left(\frac{b_i^2 k_i p_i (\alpha_i + \beta_j)^2}{2} + \frac{b_i^2 b_j^2 k_i k_j p_j (\alpha_j + \beta_i)^2 (\alpha_i + \beta_j)^2}{2(p_j^2 + k_i)}\right) \\
& (3) = \alpha_i b_i \left(\frac{b_i^2 b_j^2 k_i k_j p_i (\alpha_i + \beta_j)^2 (\alpha_j + \beta_i)^2}{2(p_i^2 + k_j)} + \frac{\alpha_i \beta_j b_i^2 k_i k_j}{p_j}\right) \\
& (4) = \alpha_i b_i \left(\frac{b_i^2 b_j^2 k_i k_j p_i (\alpha_i + \beta_j)^2 (\alpha_j + \beta_i)^2}{2(p_i^2 + k_j)} + \frac{b_i^2 b_j^2 k_i k_j p_j (\alpha_j + \beta_i)^2 (\alpha_i + \beta_j)^2}{2(p_j^2 + k_i)}\right)
\end{aligned}$$

In the setting under moral hazard, the principal can utilize the bonus coefficients α_j and β_i to provide the agents with incentives to generate more knowledge than in the single agent case. The necessary condition can be derived similar to the first-best setting and is reached when:[9]

$$\frac{\alpha_j + \beta_i}{\alpha_i + \beta_j} > \frac{b_i}{b_j} \frac{p_i}{\sqrt{k_j}}$$

To easier interpret the result, the threshold can be rearranged to: $\frac{(\alpha_j+\beta_i)b_j}{(\alpha_i+\beta_j)b_i} > \frac{p_i}{\sqrt{k_j}}$. The

[9] The equilibrium level of knowledge creation of each agent switches when $ks_i > kc_i$, so when the agent wants to share more knowledge to the other agent then he would create in his individual optimum. This threshold is reached when $\frac{\alpha_j \beta_i b_j^2 k_i k_j}{p_i} > \frac{b_i^2 k_i p_i (\alpha_i + \beta_j)^2}{2}$.

left hand side represents the additional benefit agent i receives for sharing one additional unit of knowledge whereas the right hand side represents the additional costs of doing so, which provides:

Proposition 4. *By setting the bonus coefficients* α_j *and* β_i *sufficiently high, the principal can in the multi-agent setting control each agent's proportional allocation of efforts among tasks.*

Substituting the agents' optimal effort levels ($e_i(1)$), while focusing on the case in which both agents provide the low level of knowledge creation provides the equilibrium surplus:

$$(1);\ \pi^{SB} = \frac{\alpha_i^3 b_i^4 k_i p_i}{2} + \frac{\alpha_i^2 \beta_j b_i^4 k_i k_j}{p_j} + \frac{\alpha_j^3 b_j^4 k_j p_j}{2} + \frac{\alpha_j^2 \beta_i b_j^4 k_i k_j}{p_i} - \frac{3\alpha_i^4 b_i^4 k_i p_i}{8} - \frac{\alpha_i^3 \beta_j b_i^4 k_i k_j}{2p_j} - \frac{\alpha_j^2 \beta_i^2 b_j^4 k_i k_j}{2p_i} - \frac{3\alpha_j^4 b_j^4 k_j p_j}{8} - \frac{\alpha_j^3 \beta_i b_j^4 k_i k_j}{2p_i} - \frac{\alpha_i^2 \beta_j^2 b_i^4 k_i k_j}{p_j} - \frac{r_i \alpha_i^2 \sigma_i^2}{2} - \frac{r_i \beta_i^2 \sigma_j^2}{2} - \frac{r_j \alpha_j^2 \sigma_j^2}{2} - \frac{r_j \beta_j^2 \sigma_i^2}{2}$$

Solving for the optimal bonus coefficients then results in:

Proposition 5. *Under asymmetric information, the optimal incentive coefficients are given by:*

$$\alpha_i = \frac{1}{2} - \frac{\beta_j k_j}{2p_i p_j} + \frac{1}{6k_i p_i p_j b_i^2}(30b_i^4 \beta_j k_i^2 k_j p_i p_j + 9b_i^4 k_i^2 p_i^2 p_j^2 + 9b_i^4 \beta_j^2 k_i^2 k_j^2 - 24b_i^4 \beta_j^2 k_i^2 k_j p_i p_j - 24k_i p_i p_j^2 r_i \sigma_i^2)^{0.5}$$

$$\beta_i = \frac{2\alpha_j^2 b_j^4 k_i k_j - \alpha_j^3 b_j^4 k_i k_j}{2(\alpha_j^2 b_j^4 k_i k_j + p_i r_i \sigma_j^2)}$$

Due to the strategic interaction among agents the interpretability of the optimal bonus coefficients is limited. However, from proposition 5 it is apparent that the individual bonus coefficient α_i decreases in the agent's risk aversion and the variance of his personal performance measure. The sharing incentive β_i also decreases in the agent's risk aversion and in the variance of the other agent's output measure, but increases in the marginal productivity of effort and cognitive capacity of the receiving agent.[10] Furthermore, the optimal bonus coefficient to share knowledge increases in the incentive of the receiving agent to apply the knowledge, which leads to:

Proposition 6. *An agent's motivation to share his knowledge depends upon the recipient's incentive to apply the provided knowledge, thus both the individual and the collective incentives have to be in place.*[11]

$$\frac{\partial ks_i}{\partial \alpha_i} = 0; \qquad \frac{\partial ks_i}{\partial \alpha_j} = \frac{\beta_i b_j^2 k_i k_j}{p_i} \geq 0;$$

$$\frac{\partial ks_i}{\partial \beta_i} = \frac{\alpha_j b_j^2 k_i k_j}{p_i} \geq 0; \qquad \frac{\partial ks_i}{\partial \beta_j} = 0; \qquad \frac{\partial ks_i}{\partial \alpha_j \partial \beta_i} = \frac{b_j^2 k_i k_j}{p_i} > 0$$

[10] Further effects on the optimal bonus coefficients are ambiguous.

[11] A similar result has also been reported by Siemsen et al. (2007).

This finding highlights one of the main differences of knowledge sharing compared to other team-incentive models. For example, in Auriol et al. (2002) agents can directly increase the output of other team members by providing a helping effort. Through the additive design of the model, the principal can provide incentives for each effort and each agent individually. Hence, the personal working effort and helping effort take on the form of substitutes contingent on their marginal productivities. However, knowledge does not add direct value towards an output, but only increases the recipient's productivity indirectly by lowering the disutility of effort. Thus, without an incentive to adapt and leverage the shared knowledge, the sender's sharing effort is wasted completely. Ultimately, both the sender's incentive to provide knowledge and the recipient's incentive to exert a task-related effort need to be in place. Furthermore, from proposition 6 it follows that when the incentive to support the other agent with knowledge is sufficiently high the agents will also increase their level of the knowledge creation effort to $kc_i = \frac{b_i^2 b_j^2 k_i k_j p_i (\alpha_i+\beta_j)^2(\alpha_j+\beta_i)^2}{2(p_i^2+k_j)}$ and therefore the partial derivatives from knowledge creation towards the bonus coefficients are:

$$\frac{\partial kc_i}{\partial \alpha_i} = \frac{\alpha_i b_i^2 k_i k_j p_i}{k_j + p_i^2} + \frac{\beta_j b_i^2 k_i k_j p_i}{k_j + p_i^2} \geq 0; \qquad \frac{\partial kc_i}{\partial \alpha_j} = \frac{\alpha_j b_j^2 k_i k_j p_i}{k_j + p_i^2} + \frac{\beta_i b_j^2 k_i k_j p_i}{k_j + p_i^2} \geq 0$$

$$\frac{\partial kc_i}{\partial \beta_i} = \frac{\alpha_j b_j^2 k_i k_j p_i}{k_j + p_i^2} + \frac{\beta_i b_j^2 k_i k_j p_i}{k_j + p_i^2} \geq 0; \qquad \frac{\partial kc_i}{\partial \beta_j} = \frac{\alpha_i b_i^2 k_i k_j p_i}{k_j + p_i^2} + \frac{\beta_j b_i^2 k_i k_j p_i}{k_j + p_i^2} \geq 0$$

$$\frac{\partial ks_i}{\partial \alpha_i \partial \beta_j} = \frac{b_i^2 k_i k_j p_i}{k_j + p_i^2} > 0; \qquad \frac{\partial ks_i}{\partial \alpha_j \partial \beta_i} = \frac{b_j^2 k_i k_j p_i}{k_j + p_i^2} > 0$$

Here, each derivative consists of two additive components, with the assumption that the bonus coefficients are positive an agent's incentive to generate additional knowledge increases in all available coefficients, but decreases in the private benefit of knowledge. In the earlier setting, it was shown that the degree to which employees value their skills level lowers the cost of creating knowledge. Here the decrease due to the private benefit results from the solution that the agent will share everything he knows and sharing reduces in the benefit of keeping knowledge private.

4 Extension: Effects of implementing a knowledge management system

In this setting, the principal also has the opportunity to invest into a knowledge management system (kms). Implementing a km-system has two separate effects that are analyzed individually. First, there is a cost reduction effect, which lowers the overall effort costs for sharing knowledge through the system. Second, an information effect, the new system provides the principal with an additional signal that is informative about ks_i. The signal is denoted as $z_i = ks_i$ and can be utilized for contracting. Agents receive a bonus payment denoted as γ_i for each unit of knowledge that they share when utilizing the kms. With the signal in place each agent's wage function becomes:

$$s_i(y_i, z_i) = \alpha_i \cdot y_i + \gamma_i \cdot z_i + \zeta_i$$

It is assumed that the information technology provides a perfect signal about the amount of knowledge shared. Therefore, the bonus coefficient contingent on the co-workers performance measure is no longer part of the wage function. This reduces the risk of each agent's salary as the noisy performance measure of the other agent is replaced by the reporting function of the km-system.

4.1 Benchmark solution

The benefit (cost decrease of sharing knowledge) of the information system is denoted as b_{kms}, whereas the additional costs of the system are expressed as c_{kms}. The agents can utilize the system to communicate with each other, ask questions and provide answers. This reduces the cost of participating in a knowledge exchange. The additional costs in this case can be understood as the depreciation of the financial investment in each period, which lowers the profit of the principal. The decision that is considered here, is a binary [0,1] decision of whether or not to invest in a km-system and not about how much to invest. In order to separate the impact of the investment the equilibrium solutions with and without the knowledge management system are compared. With a km-system in place the cost function of the agents changes to:

$$C_i(e_i, kc_i, ks_i) = \frac{1}{2} \cdot \left(\frac{e_i^2}{kc_i + ks_j} + \frac{kc_i^2}{k_i \cdot p_i} + \frac{ks_i^2 \cdot p_i}{k_i \cdot k_j \cdot b_{kms}} \right)$$

The principal's optimization problem is almost identical to that of the second setting, here the principal only has to bear the additional costs of the km-system (c_{kms}). Since under first-best all efforts are observable and verifiable the principal only has to pay the agents a fixed remuneration that satisfies their participation constraint. For analytical purposes the focus is set on a setting in which the agents' marginal productivities of effort are in the range that limits the amount of solutions to one. Solving the principal's optimization problem then provides:

Lemma 6. *The first-best effort levels are given by:*

$$e_i^{FB} = \frac{b_i^3 \cdot k_i \cdot (b_{kms} \cdot k_j + p_i \cdot p_j)}{2p_j}$$

$$kc_i^{FB} = \frac{b_i^2 \cdot k_i \cdot p_i}{2}$$

$$ks_i^{FB} = \frac{b_j^2 \cdot b_{kms} \cdot k_i \cdot k_j}{2 \cdot p_i}$$

and resulting equilibrium surplus equals:

$$\pi^{FB} = \frac{b_i^4 b_{kms} k_i k_j p_i + b_i^4 k_i p_i^2 p_j + b_j^4 b_{kms} k_i k_j p_j + b_j^4 k_j p_i p_j^2 - 8c_{kms} p_i p_j}{8p_i p_j}$$

In optimum the cost reduction effect (b_{kms}) increases the optimal knowledge sharing levels and in turn indirectly also the optimal level of productive efforts, which increase when agents receive additional knowledge. The resulting equilibrium surplus then increases in the benefit of the system and decreases in its costs (c_{kms}). Comparing the first-best surpluses with and without an investment into information technology provides the following condition:

Proposition 7. *When comparing the optimal results with and without the investment into a km-system, the necessary condition for implementation of a system is obtained:*[12]

$$b_{kms} \geq \frac{b_i^4 k_i k_j p_i + b_j^4 k_i k_j p_j + 8 c_{kms} p_i p_j}{k_i k_j (b_i^4 p_i + b_j^4 p_j)}$$

or, assuming that both agents are equal:

$$b_{kms} \geq 1 + \frac{4 p c_{kms}}{b^4 k^2}$$

Under the assumption that both agents are equal, the result is easily interpretable. Here, in first-best the effort levels of the agents are already observable, thus the information effect of the knowledge management system plays no role and only the cost effect is analyzed. The principal's optimal decision to implement an information technology largely depends upon three factors: i) The ratio of benefits of kms compared to the implementation costs ($\frac{b_{kms}}{c_{kms}}$). ii) If agents have a high intrinsic benefit of private knowledge they are more likely to hoard, rather than to share their expertise and the overall effect of introducing a knowledge sharing platform is reduced greatly. This solution is very intuitive, if agents are normally reluctant to share their knowledge, merely lowering the effort costs of doing so will not provide the agents with necessary incentives. This further highlights and provides a methodological explanation of the assumptions of McDermott (1999). In such a case it would be better for a company to lower the benefit of keeping knowledge private by providing long term job positions, so that employees do not hoard knowledge in order to stand out on the job market. iii) Lastly, the benefit of a knowledge management system greatly increases as the marginal productivity and cognitive capacity of agents increases. This is also quite intuitive as more productive agents can better utilize the shared knowledge.

4.2 Under Moral Hazard

For the moral hazard setting the focus is set on the case that $\frac{b_j^2}{b_i^2} > \frac{p_i^2}{k_j}$ and that agent i focuses his attention on generating and sharing knowledge with agent j. With the information system in place, the optimization problem of the principal is expressed by:

$$\max_{\alpha_i, \gamma_i} \pi = \sum_{i=1}^{n} \Big(E[(1-\alpha_i) \cdot y_i] - \gamma_i \cdot z_i \Big) - c_{kms}$$

subject to:

$$CE_i = s(y_i, z_i) - C(e_i, kc_i, ks_i) - \frac{r_i}{2} \cdot VAR(s_i) \geq 0 \qquad \text{(PC)}$$

$$e_i, kc_i, ks_i = \operatorname{argmax} CE_i \qquad \text{(IC)}$$

$$ks_i \leq kc_i \qquad \text{(SC)}$$

[12] See appendix for a proof.

with :

$$\mathrm{VAR}(s_i) = \alpha_i^2 \cdot \sigma_i^2 \qquad \forall\, i = 1, 2$$

Forming the Lagrangian of the optimization problem and solving for the optimal effort levels while excluding the solutions in which both agents provide identical effort levels provides:

Lemma 7. *The second-best effort levels are given by:*

$$e_i^{SB} = \alpha_i b_i (kc_i^{SB} + ks_j^{SB}); \qquad e_j^{SB} = \alpha_j b_j (kc_j^{SB} + ks_i^{SB})$$

$$kc_i^{SB} = \frac{k_i p_i b_{kms} k_j (\alpha_i^2 b_i^2 + \alpha_j^2 b_j^2 + 2\gamma_i)}{2(b_{kms} k_j + p_i^2)}; \qquad kc_j^{SB} = \frac{\alpha_j^2 b_j^2 k_j p_j}{2}$$

$$ks_i^{SB} = \frac{k_i p_i b_{kms} k_j (\alpha_i^2 b_i^2 + \alpha_j^2 b_j^2 + 2\gamma_i)}{2(b_{kms} k_j + p_i^2)}; \qquad ks_j^{SB} = \frac{b_{kms} k_i k_j (\alpha_i^2 b_i^2 + 2\gamma_j)}{2p_j}$$

From lemma 7 it is apparent that the degree of knowledge sharing increases in the cost reduction effect of the kms as well as the bonus payment γ_i. Substituting the agents' optimal effort levels into the principals optimization problem and solving for the bonus payments γ_i provides:

Proposition 8. *The optimal incentive bonuses for sharing knowledge are:*

$$\gamma_i = b_i^2(\alpha_i - \alpha_i^2) + b_j(\alpha_j - \alpha_j^2)$$
$$\gamma_j = b_i^2(\alpha_i - \alpha_i^2)$$

The optimal bonus coefficient for the first agent, which is set high to induce him to create additional knowledge and support the second agent, depends upon his individual incentive coefficient (α_i) and on the motivation of the other agent to apply the shared knowledge (α_j). Whereas the bonus of the second agent only depends upon the incentive coefficient of the first.[13]

5 Discussion

As outlined in the introduction and related literature review the economic understanding of appropriate incentives that enable knowledge sharing among co-workers is still limited. The present paper addresses this gap by providing a framework to analyze the interaction of employees who can create and subsequently share knowledge with one another.

The model builds upon the assumption that knowledge reduces the disutility of providing an output related effort and therefore the effect is modeled directly into the cost function of each agent. Literature suggests that knowledge reduces the time needed to complete a task (Argote and Ingram, 2000). Therefore, the effect of knowledge could arguably be modeled to enhance a worker's marginal productivity directly. Which was avoided in this

[13] A comparison of the second-best results with and without the km-system is inconclusive due to the different setups of the agents' salary functions and different utilized signals.

framework to ensure the interpretability of results. Likewise, the intrinsic benefit employees feel when keeping knowledge private is modeled as a parameter that lowers the effort costs of knowledge creation and on the other hand increases the cost for sharing knowledge with co-workers. This private benefit can be described as a feeling of power, superiority or just the general appreciation of the personal skill level. The effect of such a benefit could also be added directly to the preferences of the agent. Lee and Ahn (2007), for example, construct a concave utility function dependent upon the monopolistic knowledge of each employee. Furthermore, as a simplification it is assumed that workers do not need to exert any effort to collect shared knowledge. It is possible that equilibria exist in which one agent has a high-powered incentive to share more knowledge than another agent would be willing to absorb. On the other hand, highly skilled agents might share knowledge too complex to be absorbed by less trained agents. As discussed by Argote and Ingram (2000) not all shared insights are valuable towards the generation of outputs. When a company installs measures for knowledge sharing, but the quality of knowledge cannot be observed companies might end up with “information junkyards” (McDermott, 1999).

The main findings of the analysis are as follows: When the firm only employs a single agent, the principal cannot directly influence the agent’s level of creating additional knowledge. Only the productive output of the workers are observable and verifiable for contracting, thus the problem can be described as a multi-task setting with a single signal. Hence, the absolute level of the productive and the creative efforts can be increased or lowered, but the principal cannot control the agent’s proportional allocation of time among the different tasks (Feltham and Xie, 1994). However, this partly changes when the organization hires additional employees. When co-workers can reciprocally influence each other’s cost of effort and therefore indirectly enhance their output, additional signals become available for contracting. It is shown that the organization can choose bonus coefficients contingent upon the performance of co-workers, which leads agents to not only consider their individual optimum level of knowledge creation, but also anticipate additional benefits of sharing knowledge with co-workers. Such that if incentives to share their knowledge are sufficiently high, agents will create knowledge above their individual optimum. However, as demonstrated in the framework, knowledge itself does not add direct value towards firm performance and its benefit towards the company, similar to other scarce resources, depends upon the person that will be applying it. This differentiates the aspect of knowledge sharing from team-incentive models in which one actor can directly influence the performance of the other.

Furthermore, this leads to the interesting result that it is not necessarily in the best interest of the principal to motivate high skilled employees to provide knowledge towards low productive workers, as their opportunity costs of not focusing on the productive effort are considerably higher. Instead, the less productive worker assumes the role of a support and provides the former employee with knowledge to leverage his productivity. Which differs from the assumption in the literature that more skilled workers should be responsible to ”sharpen the skills” of less effective employees (Lee and Ahn, 2007). However, the proposed model is basically a one-shot game as the analyzed company only exists for one period and agents focus on the maximization of short term rewards. For future research of the topic, it could therefore be interesting to focus the attention on the long-term effects of knowledge sharing. They might exist an equilibrium in which it is optimal to deviate from the optimal one-shot solution to further diffuse knowledge among all employees to better leverage it in the following periods.

Finally, the extension of the model analyzes potential effects of implementing a knowledge management system. Two possible effects are considered. First, a reduction in costs can occur, as knowledge can be stored and is more easily accessible by employees, furthermore search costs of finding who knows what can be reduced. Second, the system provides an additional signal that can be utilized for contracting. In the optimal solution, the individual bonus coefficient for each agent was derived. However, this might cause complications within a firm. Companies that already utilize electronic knowledge management systems generally award bonuses that are equal for all employees that provide information and cannot set specific rewards for single agents (Davenport and Völpel, 2001). Thus in reality companies are forced to set incentives that are either too strong, or not strong enough. With this restriction the optimal solution can only be reached, as long as employees are similar in their marginal productivities of effort.

Negative effects of knowledge sharing such as sabotage or free riding have not been considered in this model, but offer avenues for future research. As with most theoretical approaches, the model is highly simplified and ignores intrinsic incentives and cultural aspects within a company. Furthermore, through the inclusion of multiple efforts that influence one another multiplicatively the interpretability of certain results is limited. Nevertheless, the analysis provides valuable insights into the knowledge sharing process and effects of monetary rewards. The theoretical predictions of the model could be further improved through empirical testing.

6 Conclusion

The proposed model provides a theoretical approach to investigate reward structures in a multi-agent setting with the goal to simultaneously motivate the agents to create, share and apply knowledge. However, knowledge is an intangible good and as such creation and sharing efforts are difficult or costly to monitor. In the single agent setting it is possible to investigate the enabling interaction of monetary incentives and private benefits of knowledge on the creative effort. Whereas, in the multi-agent setting private benefits serve as a barrier for knowledge sharing. The optimal effort level for sharing knowledge depends not only on an agent's personal incentive, but more importantly on the marginal productivity and the incentive of the other agents to efficiently apply the shared knowledge. Employees consider a trade-off between their personal productivity and private value towards their knowledge versus the cognitive capacity and productivity of the receiving agent. Knowledge itself adds no value towards firm performance but instead its worth for the organization depends upon the person that applies it to produce output. Employees that are already very productive can more effectively implement additional knowledge into their already superior work routines. Thus, it is not necessarily in the best interest of the principal to motivate skilled personnel to spend time and effort sharing knowledge with low productive workers. A consideration that is not addressed in the model is the impact of long-run concerns. Foregoing short-run benefits and spending additional effort on sharpening the skills of less productive workers might be preferred in a multi-period setting. Investments into knowledge management systems, while not motivating agents directly, increases the observability of the chosen activity levels. Furthermore, agents need less time to identify the person with relevant information, thus sharing costs also decrease.

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Appendix

Comparison of equilibrium surpluses in the first-best multi agent setting:
The four resulting equilibrium surpluses are:

$$(1) = \frac{b_i^4 k_i p_i^2 p_j + b_j^4 k_j p_i p_j^2 + b_i^4 k_i k_j p_i + b_j^4 k_i k_j p_j}{8 p_i p_j}$$

$$(2) = \frac{k_i(b_i^4 p_i^2 p_j^2 + b_i^4 k_i p_i^2 + b_i^4 k_j p_i p_j + 2b_i^2 b_j^2 k_j p_i p_j + b_j^4 k_j p_i p_j + b_j^4 k_j p_j^2 + b_j^4 k_i k_j)}{8 p_i (k_i + p_j^2)}$$

$$(3) = \frac{k_j(b_j^4 p_j^2 p_i^2 + b_j^4 k_j p_j^2 + b_j^4 k_i p_j p_i + 2b_j^2 b_i^2 k_i p_j p_i + b_i^4 k_i p_j p_i + b_i^4 k_i p_i^2 + b_i^4 k_j k_i)}{8 p_j (k_j + p_i^2)}$$

$$(4) = \frac{k_i k_j (b_i^2 + b_j^2)^2 (p_i^2 p_j + p_i p_j^2 + k_i p_i + k_j p_j)}{8(p_i^2 + k_j)(p_j^2 + k_i)}$$

When both agents are symmetrical so that $b_i = b_j, pb_i = pb_j, k_i = k_j$ it can be shown that it is optimal for the principal to set the low sharing effort. The problem reduces to:

$$(1) = \frac{2b^4kp^3 + 2b^4k^2p}{8p^2}$$

$$(2,3) = \frac{k(b^4p^4 + 6b^4kp^2 + b^4k^2)}{8p(p^2 + k)}$$

$$(3) = \frac{b^4k^2(2p^3 + 2kp)}{2(p^2 + k)^2}$$

By comparing (1) and (2, 3) the following is obtained:

$$\frac{2b^4kp^3 + 2b^4k^2p}{8p^2} > \frac{k(b^4p^4 + 6b^4kp^2 + b^4k^2)}{8p(p^2 + k)}$$

$$2b^4kp^5 + 4b^4k^2p^3 + 2b^4k^3p > b^4kp^5 + 6b^4k^2p^3 + b^4k^3p$$

$$p^4 - 2kp^2 + k^2 > 0$$

$$(-p^2 + k)^2 > 0$$

By comparing (1) and (4) the following is obtained:

$$\frac{2b^4kp^3 + 2b^4k^2p}{8p^2} > \frac{b^4k^2(2p^3 + 2kp)}{2(p^2 + k)^2}$$

$$2b^4kp^7 + 6b^4k^2p^5 + 6b^4k^3p^3 + 2b^4k^4p > 8b^4k^2p^5 + 8b^4k^3p^3$$

$$p^6 - kp^4 - k^2p^2 + k^3 > 0$$

$$(p^2 - k)^2(p^2 + k) > 0$$

Hence, under the assumption that all parameters are greater or equal to one, it can be shown that the equilibrium solutions (2,3,4) are never preferred to (1), when $\frac{b_j^2}{b_i^2} \leq \frac{p_i^2}{k_j}$.

Proof of Corollary 1:
If both agents have similar marginal productivities and cooperate, the equilibrium surplus equals:

$$\pi^{\text{exchange}} = \frac{1}{8p_jp_i}(b_i^4k_ip_i^2p_j + b_j^4k_jp_ip_j^2 + b_i^4k_ik_jp_i + b_j^4k_ik_jp_j)$$

Whereas without cooperation (knowledge hoarding), the equilibrium surplus equals:

$$\pi^{\text{hoarding}} = \frac{1}{8}(b_i^4k_ip_i + b_j^4k_jp_j)$$

Computing the difference provides:

$$\begin{aligned}\Delta\pi &= \frac{1}{8p_jp_i}(b_i^4k_ip_i^2p_j + b_j^4k_jp_ip_j^2 + b_i^4k_ik_jp_i + b_j^4k_ik_jp_j) - \frac{1}{8}(b_i^4k_ip_i + b_j^4k_jp_j)\\ &= b_i^4k_ip_i^2p_j + b_j^4k_jp_ip_j^2 + b_i^4k_ik_jp_i + b_j^4k_ik_jp_j - b_i^4k_ip_i^2p_j - b_j^4k_jp_ip_j^2\\ &= b_i^4k_ik_jp_i + b_j^4k_ik_jp_j\end{aligned}$$

Proof of Proposition 7:
When comparing the equilibrium surpluses with and without the knowledge management system, the following is obtained:

$$\pi^{\text{kms}} = \frac{b_i^4b_{\text{kms}}k_ik_jp_i + b_i^4k_ip_i^2p_j + b_j^4b_{\text{kms}}k_ik_jp_j + b_j^4k_jp_ip_j^2 - 8c_{\text{kms}}p_ip_j}{8p_ip_j}$$

$$> \pi^{\text{no kms}} = \frac{b_i^4k_ip_i^2p_j + b_j^4k_jp_ip_j^2 + b_i^4k_ik_jp_i + b_j^4k_ik_jp_j}{8p_ip_j}$$

$$b_i^4b_{\text{kms}}k_ik_jp_i + b_j^4b_{\text{kms}}k_ik_jp_j > b_i^4k_ik_jp_i + b_j^4k_ik_jp_j + 8c_{\text{kms}}p_ip_j$$

$$b_{\text{kms}} > \frac{b_i^4k_ik_jp_i + b_j^4k_ik_jp_j + 8c_{\text{kms}}p_ip_j}{k_ik_j(b_i^4p_i + b_j^4p_j)}$$

Note: This solution holds for a comparison of any of the four equilibrium surpluses.

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