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An inspection game of internal audit and the influence of whistle-blowing

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Abstract In this paper we analyse how whistle-blowing affects fraudulent behaviour of managers while the company instigates imperfect internal audit to detect the fraud. To do so, we employ in a first step a non-cooperative inspection game to analyse fraudulent behaviour of a manager controlled by an internal auditor. In a second step we introduce exogenous whistle-blowing of a manager's employee to aid the auditor to reveal the fraud. In a third step, the two-person inspection game is extended to a three-person approach with endogenous whistle-blowing. Our novel results are that the intensity of internal audit is always lower with whistle-blowing than without and that whistle-blowing renders the manager to act less fraudulently than compared to the basic inspection game if and only if she is unaware of the whistle-blower's expected pay-off and the efficacy of internal audit is sufficiently low.

Keywords Whistle-blowing · Inspection game · Three-preson game

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1 Introduction

1.1 Motivation

By employing game theory, Fandel (1979) shows that the optimality of decision processes within organizations is a key factor in business processes. In the sense of e.g. Fandel and Trockel (2013), this optimality can be jeopardised by employees or managers who may strive to achieve individually optimal goals rather than targets that are optimal for the company as a whole and, hence, abuse the board's trust in them, see Güth and Kliemt (2007). At this, Küpper (2007) stresses that companies are constantly confronted with moral problems as managers may find it acceptable to be corruptive or act fraudulently for their own good. Recent empirical evidences for this are the faked emission numbers of Volkswagen revealed in 2015, the LIBOR scandal disclosed in 2011 involving traders of e.g. the Deutsche Bank or the scandal of Siemens' managers and sales staff bribing government officials. As a consequence, regulators and auditing standard boards have tried to improve corporate governance systems during the last years by means of defining compliance rules. Examples for this are the Dodd-Frank-Act (2010), the updated Internal Control Framework of the Committee of Sponsoring Organizations of the Treadway Commission (2013) or the three lines of defence model of The Institute of Internal Auditors (2013).

Besides the regulatory framework, firms invest considerably in the prevention and detection of fraud (Liekweg 2014). According funds not only go to internal control mechanism via internal auditing, but also to company-internal ethics programs. These can be seen as a key element of an ethical culture where respective formal training is intended to foster compliant behaviour of managers (Schwartz 2013). In view of the efficacy of this formal training, Malmstrom and Mullin (2013) show by means of anonymous exit surveys that violations of the code of ethics is tolerated by a significant amount of participants. Hildreth et al. (2016) furthermore show that the content of the code of ethics is of vital importance. They establish that if formal training conveys loyalty towards the company as part of the code, managers act fraudulently more likely. Taken together, it can be expected that fraudulent behaviour of managers will not cease to exist.

To encourage employees of a fraudulent manager to provide respective information, companies implement e.g. an internal whistle-blower hotline, where audit committee chairs typically consider the internal audit to administer such a system (Soh and Martinov-Bennie 2011). Given this point of contact, the information transfer from the whistle-blower to the auditor is found to be successful if anonymous reporting, organizational support as well as strong monetary incentives are granted to the former (Lee and Fargher 2013). This company-internal support, however, is prone to not completely take account of probable costs for whistle-blowers, as e.g. the identity of the latter may leak to others (Dyck et al. 2010). Consequences thereof can be seen in the whistle-blower being dismissed by the fraudulent manager as well as in social costs arising from the harassment of colleagues or from public interest if the whistle-blower's identity is leaked outside the company (Crook 2000). An empirical example is the case of Jesselyn Radack, a former employee of the US Ministry of

Justice. As a whistle-blower, her identity leaked to the public in 2002 due to which she experienced severe personal repercussion including a miscarriage.

1.2 A literature overview

Corruptive or illegal behaviour and antitrust is a common issue in economics literature. As fundamental literature on fraud in economics, Abbink (2006) has to be mentioned, who surveys various factors of influence regarding fraudulent behaviour. Christöfl et al. (2017) analyse via an experimental study the influence of bribes offered to an employee of a company, the detection probability thereof and a principal witness policy. They establish that the number of offered bribes is the lower, the more lenient the witness policy. Furthermore, it is shown that while there may be fewer bribes, a more pronounced leniency results in higher incentives for corruptive bidders. Ewelt-Knauer et al. (2015) show empirically that the revelation of fraudulent behaviour exerts a strong negative influence on both the wealth of shareholders and—depending on the specific characteristics of the fraud—also on investors.

In particular, several contributions address intra- and inter-organizational corruption control elements (e.g. Basu et al. 2016; Barnejee 1997; Khalil and Lawarree 2006; Khalil et al. 2010). Whistle-blowing as a relevant measure against illegal behaviour is, however, discussed only in some cases. An extensive survey thereof with the focus on whistle-blowing based on empirical and experimental evidence can be found in Marvao and Spagnolo (2014). Spagnolo (2008) surveys the theoretical discussion of antitrust legislation to impede illegal cartel formation and criminal activities of organizations. In the context of trust, leniency and deterrence, Bigoni et al. (2015) focus on reporting, finding and possible funding of fraud. Recently, Beim et al. (2014) discuss whistle-blowing and compliance in the judicial hierarchy. In a non-cooperative game, they show that the problem of compliance can be reduced by the presence of a whistle-blower at the lower courts level. Moreover, a whistle-blower with the characteristics of a "perfect ally" is not rational, because the whistle is blown too often.

Next to these approaches partly adapted by experiments, whistle-blowing of wrongdoing within firms and in other contexts are analysed via (laboratory) experiments by Abbink and Wu (2017), Breuer (2013), Schmolke and Utikal (2016), Reuben and Stephenson (2013) and Bartuli et al. (2016) to show the relevance of a discussion of whistle-blowers in organizational industries.

A current study of Mechtenberg et al. (2017) combines whistle-blower protection in theory and experimental evidence. They model whistle-blower protection within a game theoretic approach, where the strategic players are represented by a possibly fraudulent employer, an employee and a prosecutor. The focus is on the problem of whether there is a whistle-blowing employee or not and whether there is protection from being dismissed or not. They find that if the whistle is blown and protection is easily obtained through a reasonable belief of the employee about the fraud, the issue of false claims by the employee becomes considerable. As a consequence, the prosecutor is less willing to investigate. If, however, protection is granted after the verification of the employee's claim, the former undesired effects of protection are alleviated.

Chassang and Padro i Miquel (2014) address a cheap-talk game with endogenous actions of misbehaviour, reporting (truthfully) and investigating by three strategic players: a (non-)corruptive employer (agent), a monitor, who observes corruption and sends a statement to the principal, as well as the principal herself, who takes account of the monitor's statement and maybe triggers an investigation. By doing so, they establish a correlation between corruption and whether or not a statement is verifiable.

In the present analysis, we combine the problem of whistle-blowing and an inspection game in economics. An inspection game (IG) as first considered by Dresher (1962) can be described as a decision making model involving a vertical conflict between an inspection authority and an agent (state or organisation). The latter features a contractual commitment to comply with regulations while the inspector has to execute monitoring measures in order to guarantee that the inspectee behaves in conformity with the given rules. The IG is applied in economics, especially in auditing or intra-organisational conflicts, see Trockel (2013) for an extensive survey. In various research fields there exist publications based on the idea of Dresher (1962) at smuggling, see Hohzaki and Masuda (2012), at crime fighting, see Andreozzi (2010), or at corruption, see Friehe (2008). Berentsen et al. (2008) consider an inspection game in sports, where the beaten actor can blow the whistle to a controller, who may trigger a doping screening. Intra-organisational conflicts in economics with respect to an IG, which will be the basis of the following decision model, are addressed first by Borch (1982) and in the last years especially by Fandel and Trockel (2013) and Trockel (2013), who analyse a three-person inspection game with one employer, one controller and the board. The former focus on the influence of pay-off parameters (bonuses and penalties), that may counteract each other, on the Nash equilibrium. The latter analyses corresponding second-order effects.

Bone and Spengler (2014) combine corruption and inspection strategies in a game theoretical model based on the considerations of Tsebelis (1989, 1990, 1995). They focus on a potential briber, an official, who can accept or reject corruptive behaviour of the briber, and an inspector, who can control them or not. They extend the basic model by reporting of the official. Their contribution contains interesting results: A higher official's punishment decreases corruptive behaviour, but higher briber's punishment increases the overall probability of corruptive behaviour.

1.3 Aim and contribution of the analysis

Generally, IGs focus on solving problems arising from inter- and intra-organisational interactions. The following analysis addresses the influence of (im-)perfect information on potential whistle-blowers extending an IG with a (corruptive) manager and an internal auditor. As stated above, e.g. based on the collapse of Lehman, internal auditing is implemented in companies as direct subordinate to the board to ensure good corporate governance. We, therefore, disregard external auditing (Fandel and Trockel 2011b) and controlling (Fandel and Trockel 2011a), as they discharge deviating tasks for a company and, hence, are a point of contact of second rank if an employee decides to blow a whistle. As in Beim et al. (2014), we take up the compliance problem within a company.

It should be clear, though, that a single and possible fraudulent manager typically is the supervisor of other employees that have access to (at least incomplete) information about the manager's questionable behaviour. The fraudster should, thus, anticipate that in one way or another, there is the risk that other persons within the company may disclose the fraud to the internal audit, such that the manager can be hold responsible for her actions. At this, whistle-blowing as a detection device can clearly be attributed to and supported by a fraud-averse ethical culture. We focus on internal audit and the problem of being active (whistle-blowing) or staying passive (being quiet) given potential corruptive behaviour in one company.

Our analysis of whistle-blowing is based on Berentsen et al. (2008) as well as Mechtenberg et al. (2017), and contributes to the literature by extending a typical inspection game approach as in e.g. Friehe (2008) and Fandel and Trockel (2011a) to a simultaneous game of three strategic players: one (non-)corruptive manager, one auditor that monitors the manager either thoroughly to possibly detect the fraud or not as well as one employee of the manager's department that either blows the whistle of the manager's fraud or stays passive. Our approach, thus, also adds to the literature on the prevention and detection of fraud (e.g. Doyle et al. 2007; Hoffman and Zimbelman 2009; Masli et al. 2010). A prosecutor like in Mechtenberg et al. (2017) is not considered for the focus on company-internal mechanisms of sanctions. Our approach differs from that in Chassang and Padro i Miquel (2014), who discuss a principal triggering an investigation or not, as we focus on corporate fraud like in the scandals involving VW or Siemens, where we deem the chance of whistle-blowing of employees a realistic assumption. At this, we take account that blowing the whistle also constitutes a risk for an employee herself, because e.g. the resulting fine imposed on the department she works for can affect her job as well.

We obtain results that, on the one hand, are plausible but, on the other hand, are surprising from an economic point of view. In particular, we show that whether the manager and auditor can influence the choice of the whistle to be blown or not leads to two opposing outcomes. We set forth a benchmark non-cooperative inspection game in Sect. 2 involving a manager and an internal auditor. In a next step we introduce whistle-blowing to the benchmark setting in Sect. 3, where the manager and auditor treat the chance of whistle-blowing as given. Eventually, we modify the benchmark two-person inspection game by incorporating the endogenous choice of whistle-blowing in Sect. 4. Section 5 concludes.

2 The benchmark auditor-manager inspection game of internal control

We assume an inspection game of risk-neutral players. In particular, we consider a company, in which the board, i.e. the principal, and a representative manager, i.e. the agent, exhibit conflicting goals in that the former aims at maximising the company's long-term profit while the latter strives to maximise its short-term pay-off. In doing so, the manager accepts fraud as a possible mean to increase her revenues via not complying with law or company's policies. Since the board, by assumption, fails to detect fraudulent behaviour, it employs an internal auditor, who is likely able to do so (Hillison et al. 1999). She truthfully reports her findings to the board and is delegated to monitor the manager.

Each player is considered to have two strategic alternatives. The manager decides whether or not to be fraudulent. That is, she plays *fraud* with probability p_f and *no fraud* with counter probability $(1 - p_f)$. The internal auditor chooses between conducting a thorough, i.e. *high level*, inspection with probability p_h, which is able to detect fraudulent behaviour with a given probability p_r, or *standard level* auditing with counter probability $(1 - p_h)$, which does not. We assume that p_r captures that even a high level inspection may be prone to e.g. technical or communication deficiencies the inspector cannot control, which render the result of the inspection invalid in terms of falsely certifying the board non-fraudulent behaviour of the manager when it is in fact fraudulently.

To determine the strategy-dependent pay-off of the manager, suppose that the auditor chooses standard level auditing. Given that the manager does not act fraudulently, her usual basic salary accrues, which for simplicity is set to zero. If the manager acts fraudulently, she receives the according benefit Γ. However, since illegal behaviour will become apparent in the long run, the manager will receive a reputation loss in the future (Ewert 1993). Its present value is denoted by ρ^- and we assume that the actual reputation loss occurs at a certain point in time, where the manager cannot be legally hold responsible for its fraud, as the limitation period is expired. Hence, the manager's pay-off in case of (fraud/standard level) is $\Gamma - \rho^-$.

Provided that the internal auditor chooses high level auditing, the manager always experiences audit costs κ, as she has to spend more time in providing data to the auditor. Also, if she does not act fraudulently, she receives her basic salary of zero. If she acts fraudulently, in turn, she earns her fraud benefit Γ. Additionally, if high level auditing does not detect the fraud, she experiences the long-term reputation loss ρ^-. Given that the auditor reveals the fraud, there arise costs for the manager in terms of e.g. losing her job, having difficulties in finding a new occupation as well as being legally held responsible for her fraud. We denote these costs by Δ, which intuitively exceed ρ^-, i.e.

$$\Delta > \rho^- \tag{1}$$

and also assume that they exceed the benefit of fraudulent behaviour in terms of

$$\Delta > \Gamma. \tag{2}$$

The manager's pay-off subject to the certain strategy tuple (fraud/high level), then, amounts to $\Gamma + p_r \cdot (-\Delta) + (1 - p_r) \cdot (-\rho^-) - \kappa$. For the following analysis, let

$$\mathcal{A}^M \equiv \Gamma + p_r \cdot (-\Delta) + (1 - p_r) \cdot (-\rho^-) - \kappa, \tag{3}$$

$$\mathcal{B}^M \equiv \Gamma - \rho^-, \tag{4}$$

$$\mathcal{C}^M \equiv -\kappa, \tag{5}$$

$$\mathcal{D}^M \equiv 0, \tag{6}$$

such that the expected pay-off of the manager, π^M, is given by

$$\pi^M = p_f \cdot \left[p_h \cdot \mathcal{A}^M + (1-p_h) \cdot \mathcal{B}^M\right] + (1-p_f) \cdot \left[p_h \cdot \mathcal{C}^M + (1-p_h) \cdot \mathcal{D}^M\right]. \tag{7}$$

In view of the auditor, we generally assume that standard level auditing is costless and high level auditing involves costs K, which stem e.g. from the auditor's need to increase her staffing or to spend more time in thoroughly checking the data provided by the manager. Given that the manager does not act fraudulently and the auditor chooses the standard level, the latter is, furthermore, assumed to gain her salary also set to zero for simplicity. If, instead, the high level is chosen, there occur the costs of high level auditing K, as well. Given that the manager acts fraudulently, the standard level is unable to detect the fraud. As illegal behaviour will become apparent in the long run, the auditor will be held responsible for not exposing the fraud in the future and experiences an according reputation loss denoted by R^-. In contrast to the standard level, high level auditing may detect the fraud. If it does so, the auditor earns a reputation gain represented by R^+. In case that it does not, the reputation loss R^- arises like with standard level auditing. The pay-off of the auditor given (fraud/high level) is thus given by $p_r \cdot R^+ + (1-p_r) \cdot (-R^-) - K$. To simplify the following discussion, let

$$\mathcal{A}^A \equiv p_r \cdot R^+ + (1-p_r) \cdot (-R^-) - K, \tag{8}$$

$$\mathcal{B}^A \equiv -R^-, \tag{9}$$

$$\mathcal{C}^A \equiv -K, \tag{10}$$

$$\mathcal{D}^A \equiv 0. \tag{11}$$

The auditor's expected pay-off, thus, reads

$$\pi^A = p_f \cdot \left[p_h \cdot \mathcal{A}^A + (1-p_h) \cdot \mathcal{B}^A\right] + (1-p_f) \cdot \left[p_h \cdot \mathcal{C}^A + (1-p_h) \cdot \mathcal{D}^A\right]. \tag{12}$$

In the inspection game considered, both the manager and the auditor maximise their respective expected pay-off from (7) and (12) in a simultaneous one-shot game for a given strategy choice of the other player. That is,

$$\max_{p_f} \pi^M \quad \text{and} \quad \max_{ph} \pi^A$$

subject to

$$\mathcal{A}^M < \mathcal{C}^M \quad \Leftrightarrow \quad \Gamma + p_r \cdot (-\Delta) + (1-p_r) \cdot (-\rho^-) < 0, \tag{13}$$

$$\mathcal{B}^M > \mathcal{D}^M \quad \Leftrightarrow \quad \Gamma - \rho^- > 0, \tag{14}$$

$$\mathcal{A}^A > \mathcal{B}^A \quad \Leftrightarrow \quad p_r \cdot (R^+ + R^-) - K > 0, \tag{15}$$

$$\mathcal{C}^A < \mathcal{D}^A \quad \Leftrightarrow \quad -K < 0, \tag{16}$$

which ensure that there is no Nash (1951) equilibrium in pure strategies. Solving the optimization problem gives

$$p_h^* = \frac{\Gamma - \rho^-}{p_r \cdot (\Delta - \rho^-)}, \tag{17}$$

$$p_f^* = \frac{K}{p_r \cdot (R^+ + R^-)}, \tag{18}$$

where here and below an asterisk indicates equilibrium quantities. Because of (1) and (13) to (16), we also find that $p_f^*, p_h^* \in (0, 1)$.

A comparative static analysis of (17) and (18) results in

$$\text{(a)}: \ \frac{\partial p_h^*}{\partial \Gamma} > 0, \qquad \text{(b)}: \ \frac{\partial p_h^*}{\partial \Delta}, \frac{\partial p_h^*}{\partial \rho^-}, \frac{\partial p_h^*}{\partial p_r} < 0 \tag{19}$$

and

$$\text{(a)}: \ \frac{\partial p_f^*}{\partial K} > 0, \qquad \text{(b)}: \ \frac{\partial p_f^*}{\partial R^+}, \frac{\partial p_f^*}{\partial R^-}, \frac{\partial p_f^*}{\partial p_r} < 0. \tag{20}$$

The intuition for (19) (a) is that a higher Γ raises the manager's willingness to act fraudulently, as her according net benefit grows. The auditor counteracts this by means of more likely high level auditing. (19) (b) shows that the willingness for high level auditing is the lower, the higher the costs borne by the manager in case of fraudulent behaviour (Δ and ρ^-) and the higher the detection probability of high level auditing (p_r). At this, the auditor anticipates that an increase in either parameter renders the fraud less profitable for the manager, such that the latter's willingness to act accordingly shrinks.

It can be seen from (18) (a) that the manager chooses fraud the more likely, the higher the auditor's costs of high level auditing. As a higher K is tantamount to a reduction of the net benefit of high level auditing revealing the fraud, the auditor chooses the respective strategy less likely. Hence, fraudulent behaviour is detected less likely, as well, and the manager's willingness for fraud increases. Moreover, (20) (b) connotes that a rise in the auditor's reputation gain from high level auditing revealing the fraud (R^+) and in the reputation loss from not revealing the fraud although possible (R^-) lowers the willingness of the manager to act fraudulently. Intuitively, the manager anticipates that a growth in the auditor's net benefit of successful high level auditing as well as a rise in her punishment of failing to reveal the fraud causes the auditor to increase her efforts. Hence, her willingness for high level auditing to counteract the fraud becomes greater. Also from (20) (b), we find that the manager takes into account that a higher detection probability (p_r) increases the

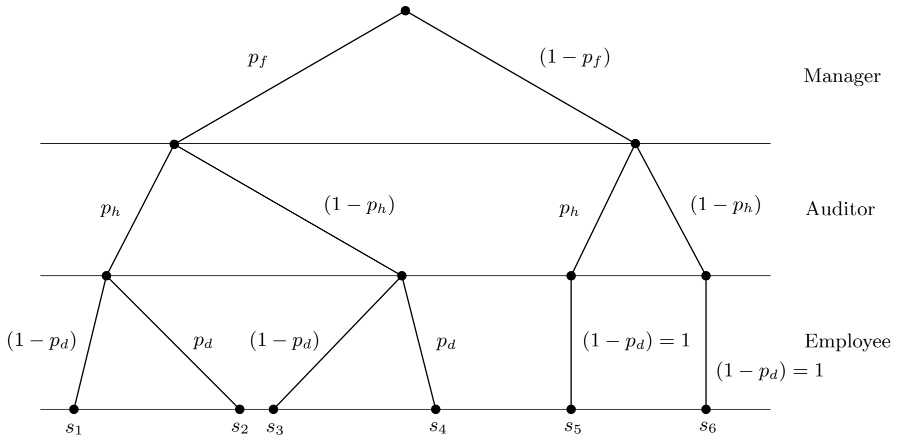

Fig. 1 Game tree including the decisions of the manager, auditor and employee

efficacy of high level auditing, such that fraud is more likely detected. As a consequence, the manager lowers her willingness to act fraudulently.

3 The auditor-manager inspection game of internal control with exogenous whistle-blowing

In this section, we utilize the idea of whistle-blowing in an inspection game. We extend the inspection game from Sect. 2 by the possibility that within the team of the manager, there is a team member (henceforth referred to as employee) who knows about the manager's fraud if it is conducted and may reveal it to the auditor as her closest contact person. It is considered that the employee discloses the manager's fraud to the auditor with exogenous probability p_d and hides it with counter probability $(1-p_d)$. Note that by considering the employee's decisions as given, we assume that, on the one hand, the manager and auditor are perfectly aware of the disclosure choice of the employee being an element of $p_d \in (0,1)$. On the other hand, the present approach can be understood as the auditor's and manager's decision having no influence on the employee's choice of whether or not to blow the whistle.

Taking account of the strategies of the manager and auditor, we generally illustrate the present game for a given decision of the employee in Fig. 1. The end nodes represent the strategy tuples following from the choices of the players, such that e.g. s_3 = (fraud/low level/hide). Note that given non-fraudulent behaviour of the manager, there is no scope for the employee disclosing any fraud and the respective strategy tuples each are an empty set. Hence, the employee only decides in favour of hide with certainty, i.e. $(1-p_d)=1$.

The strategy-dependent pay-offs are presented in Table 1, where we use a tilde in order to identify quantities in the present setting. They read as follows. Suppose, first, that the manager acts non-fraudulently. Then, her pay-off depending on

Table 1 Bimatrix of the manager's and auditor's strategy dependent pay-offs for a given disclosure decision p_d of the employee

Manager / Auditor	High level $\tilde{p}_h$	Low level $(1-\tilde{p}_h)$
Fraud $\tilde{p}_f$	$(1-p_d)\cdot\mathcal{A}^M + p_d\cdot\mathcal{A}_d^M$	$(1-p_d)\cdot\mathcal{B}^M + p_d\cdot\mathcal{B}_d^M$
	$(1-p_d)\cdot\mathcal{A}^A + p_d\cdot\mathcal{A}_d^A$	$(1-p_d)\cdot\mathcal{B}^A + p_d\cdot\mathcal{B}_d^A$
No fraud $(1-\tilde{p}_f)$	$\mathcal{C}^M$	$\mathcal{D}^M$
	$\mathcal{C}^A$	$\mathcal{D}^A$

the audit level choice is the same as before, since potential whistle-blowing has no impact on legal behaviour. The manager, therefore, gains $\mathcal{C}^{\mathcal{M}}$ from (5) in case of high level auditing and $\mathcal{D}^M$ from (6) given a low level audit.

Second, consider that the manager acts fraudulently and the employee reveals the fraud by providing respective information to the auditor. If high level auditing is chosen, the audit report reveals the fraud with certainty. Hence, $p_r = 1$ applies and the manager's pay-off amounts to

$$\mathcal{A}_d^M \equiv \Gamma - \Delta - \kappa. \tag{21}$$

Given whistle-blowing, the fraud is also detected in case of low level auditing without the emergence of high level audit costs, such that the manager gains

$$\mathcal{B}_d^M \equiv \Gamma - \Delta. \tag{22}$$

The expected pay-off of the manager with whistle-blowing, $\tilde{\pi}^M$, is consequently given by

$$\begin{aligned}\tilde{\pi}^M = \tilde{p}_f \cdot \Big[\tilde{p}_h \cdot \Big((1-p_d)\cdot\mathcal{A}^M + p_d\cdot\mathcal{A}_d^M\Big) + (1-\tilde{p}_h)\cdot\Big((1-p_d)\cdot\mathcal{B}^M + p_d\cdot\mathcal{B}_d^M\Big)\Big] \\ +(1-\tilde{p}_f)\cdot\Big[\tilde{p}_h\cdot\mathcal{C}^M + (1-\tilde{p}_h)\cdot\mathcal{D}^M\Big].\end{aligned} \tag{23}$$

In view of the auditor, note that in case of fraudulent behaviour of the manager and no disclosure of the employee, her pay-off in case of high and low level auditing is the same as defined in Sect. 2, i.e. $\mathcal{A}^A$ and $\mathcal{B}^A$ from (8) and (9). If the employee discloses the manager's fraud and the auditor applies high level auditing, her certain detection of the fraud results in her reputation gain minus the high level audit costs, i.e.

$$\mathcal{A}_d^A \equiv R^+ - K \tag{24}$$

with $\mathcal{A}_d^A > 0$. Provided that the auditor chooses low level auditing, the employee's disclosure of the fraud also leads to the detection of the manager's fraud. However, we assume that the board is aware that the audit has been successful only due to the employee blowing the whistle, whereas otherwise it would have failed.[1] The

[1] Note that this assumption does not connote that the employee's identity is or becomes known to the board. That is, given a truthful report by the internal auditor to the board, the auditor only confirms that her successful identification of fraudulent behaviour was possible only due to some kind of 'company-internal help'.

reputation gain of the auditor is, therefore, smaller than in case of high level auditing. This is formally grasped by

$$\mathcal{B}_d^A \equiv z \cdot R^+ \quad \text{with} \quad z \in (0,1). \tag{25}$$

Eventually, be aware that in case of non-fraudulent behaviour of the manager, nothing changes with respect to the auditor's pay-off and she receives $\mathcal{C}^A$ from (10) given high level auditing and $\mathcal{D}^A$ from (11) given low level auditing. In total, the expected pay-off of the auditor with whistle-blowing, $\tilde{\pi}^A$, amounts to

$$\begin{aligned}\tilde{\pi}^A \;&= \tilde{p}_f \cdot \left[\tilde{p}_h \cdot \left((1-p_d)\cdot \mathcal{A}^A + p_d \cdot \mathcal{A}_d^A\right) + (1-\tilde{p}_h)\cdot\left((1-p_d)\cdot \mathcal{B}^A + p_d \cdot \mathcal{B}_d^A\right)\right] \\ &\quad + (1-\tilde{p}_f)\cdot\left[\tilde{p}_h \cdot \mathcal{C}^A + (1-\tilde{p}_h)\cdot \mathcal{D}^A\right].\end{aligned} \tag{26}$$

The manager and auditor maximise their respective expected pay-offs subject to Nash conjectures for a given disclosure probability p_d in terms of

$$\max_{\tilde{p}_f} \tilde{\pi}^M \quad \text{and} \quad \max_{\tilde{p}_h} \tilde{\pi}^A.$$

To avoid corner solutions in pure strategies in the inspection game, the optimization problem is solved subject to (16) and

$$\begin{gathered}(1-p_d)\cdot \mathcal{A}^M + p_d \cdot \mathcal{A}_d^M < \mathcal{C}^M \\ \Leftrightarrow \\ \Gamma + \left[(1-p_d)\cdot p_r + p_d\right]\cdot(-\Delta) + (1-p_d)(1-p_r)\cdot(-\rho^-) < 0,\end{gathered} \tag{27}$$

$$(1-p_d)\cdot \mathcal{B}^M + p_d \cdot \mathcal{B}_d^M > \mathcal{D}^M \quad \Leftrightarrow \quad \Gamma + p_d\cdot(-\Delta) + (1-p_d)\cdot(-\rho^-) > 0, \tag{28}$$

as well as

$$\begin{gathered}(1-p_d)\cdot \mathcal{A}^A + p_d \cdot \mathcal{A}_d^A > (1-p_d)\cdot \mathcal{B}^A + p_d \cdot \mathcal{B}_d^A \\ \Leftrightarrow \\ (1-p_d)\cdot\left[p_r\cdot(R^+ + R^-) - K\right] + p_d\cdot\left[(1-z)\cdot R^+ - K\right] > 0.\end{gathered} \tag{29}$$

Notice that due to (1), on the one hand, (27) is more restrictive than (13). On the other hand, (27) and (28) do not contradict each other. Be also aware that (29) is satisfied if

$$z < \min\left\{1,\; 1 + \frac{(1-p_d)\cdot p_r\cdot(R^+ + R^-) - K}{p_d \cdot R^+}\right\}, \tag{30}$$

which generally ensures that the auditor has an incentive to play high level in the first place.

In the Nash equilibrium, we obtain the probabilities

$$\tilde{p}_h^* = \frac{\Gamma - \rho^- - (\Delta - \rho^-) \cdot p_d}{p_r \cdot (\Delta - \rho^-) \cdot (1 - p_d)}, \tag{31}$$

$$\tilde{p}_f^* = \frac{K}{(1 - p_d) \cdot p_r \cdot (R^+ + R^-) + p_d \cdot (1 - z) \cdot R^+}. \tag{32}$$

Notice that $\tilde{p}_h^* \in (0, 1)$ holds because of (1), (27) and (28). Moreover, $\tilde{p}_f^* \in (0, 1)$ is due to (16) as well as (29) together with (30).

The comparative static analysis of (31) and (32) with respect to the parameters addressed in (19) and (20) yields the qualitatively same results as discussed there and is omitted. Verifying the influence of p_d and z on the Nash equilibrium in (31) and (32) gives[2]

$$\frac{\partial \tilde{p}_h^*}{\partial p_d} < 0 \tag{33}$$

and

$$\text{(a)}: \ \frac{\partial \tilde{p}_f^*}{\partial p_d} \begin{Bmatrix} > \\ < \end{Bmatrix} 0 \quad \text{if} \quad p_r \begin{Bmatrix} > \\ < \end{Bmatrix} \frac{(1 - z) \cdot R^+}{R^+ + R^-}, \qquad \text{(b)}: \ \frac{\partial \tilde{p}_f^*}{\partial z} > 0. \tag{34}$$

(33) shows that the higher the probability of disclosing the manager's fraudulent behaviour, the lower the willingness of the auditor to apply high level auditing. This is driven by substitutionality of disclosing the fraud and high level auditing from the company's perspective. According to (34) (a), the willingness of the manager for fraudulent behaviour is the higher (lower), the higher p_d only if the efficacy of high level auditing in absence of whistle-blowing in terms of p_r is sufficiently high (low). To understand the mechanism behind this result, take into account that, on the one hand, the manager anticipates (33), which tends to increase her willingness to act fraudulently as the auditor reveals the fraud less likely without whistle-blowing. On the other hand, a higher p_d induces the manager to reduce her probability for fraudulent behaviour due to a more likely disclosure of her fraud to the auditor. As shown by (34) (a), the former effect dominates (is dominated by) the latter if the high level audit without disclosure is sufficiently effective (ineffective). Then, the manager puts comparatively more (less) weight on the chance that the whistle is not blown and the auditor fails to reveal the fraud.

(34) (b) connotes that the probability of choosing fraud increases in the share z, which is found in the auditor's pay-off if low level auditing reveals the fraud due

[2] In the Appendix, we present all comparative static results regarding (31) and (32).

to the employee blowing the whistle, i.e. $z \cdot R^{+}$. Since a rise in z is tantamount to an respective pay-off increase, her willingness for low level auditing increases. The according reaction of the manager is to act fraudulently with a higher probability, as there still is the chance that the employee does not blow the whistle and the fraud is not revealed by the internal audit.

To figure out in what way exogenous whistle-blowing affects the Nash equilibrium of the benchmark inspection game from Sect. 2, we compare respective equilibrium probabilities from (17), (18), (31) and (32). This results in

Proposition 1 *If there is exogenous whistle-blowing,*

(i) *the auditor is less willing to apply high level auditing than in absence of whistle-blowing, i.e.*

$$\tilde{p}_h^* < p_h^*.$$

(ii) *the manager is less (more) willing to act fraudulently than in absence of whistle-blowing if the detection probability p_r is sufficiently low (high), i.e.*

$$\tilde{p}_f^* \begin{Bmatrix} > \\ < \end{Bmatrix} p_f^* \quad \text{if} \quad p_r \begin{Bmatrix} > \\ < \end{Bmatrix} \frac{(1-z) \cdot R^+}{R^+ + R^-}.$$

Proof See the Appendix.

Proposition 1 (i) is based on the fact that from the company's perspective, whistle-blowing serves as a substitute for high level auditing by means of the employee taking on a relevant role in the internal control environment (Read and Rama 2003). Hence, if the employee shares her information about a fraud, there is less need for high level auditing. The rationale for proposition 1 (ii) follows the idea of the intuition of (34) (c). Being aware of the result in (i), the manager is more willing to act fraudulently with exogenous whistle-blowing than without, if high level auditing with the employee hiding the fraud is sufficiently effective (p_r is sufficiently high). Then, since the probability of high level auditing is lower than in the benchmark case, the manager deems it more important that in case of the employee not blowing the whistle, there is a greater chance that her fraud is not revealed. Otherwise, if p_r sufficiently low, the manager's choice in comparison to the benchmark setting is mainly driven by the risk, that her fraud can be disclosed to the auditor, such that she chooses fraud less likely.

4 The three-person inspection game with endogenous whistle-blowing

As the final step of our analysis, we endogenise the disclosure decision of the employee and, hence, modify the above considered typical two-person inspection game to a three-person approach with simultaneous decisions of all players. The strategy-dependent pay-offs of the manager and auditor remain the same as in

Table 2 Polymatrix of the three players' strategy dependent pay-offs

Manager Auditor Employee		High level $\hat{p}_h$	Low level $(1-\hat{p}_h)$
Fraud $\hat{p}_f$	Hide $(1-\hat{p}_d)$	$\mathcal{A}^M$	$\mathcal{B}^M$
		$\mathcal{A}^A$	$\mathcal{B}^A$
		$\mathcal{A}^E$	$\mathcal{B}^E$
	Disclose $\hat{p}_d$	$\mathcal{A}_d^M$	$\mathcal{B}_d^M$
		$\mathcal{A}_d^A$	$\mathcal{B}_d^A$
		$\mathcal{A}_d^E$	$\mathcal{B}_d^E$
No fraud $\hat{p}_f$	Hide $(1-\hat{p}_d)=1$	$\mathcal{C}^M$	$\mathcal{D}^M$
		$\mathcal{C}^A$	$\mathcal{D}^A$
		$\mathcal{C}^E$	$\mathcal{D}^E$

Sect. 3, whereas the pay-off components of the employee have to be determined. To do so, recall the game tree from Fig. 1 upon which we assign the players' pay-offs in Table 2. We use a hat to distinguish the according probabilities from those in the previous discussion.

The strategy-dependent pay-offs of the employee grounds on the following idea. We assume that she generally receives her basic salary v. In case that the manager and the auditor play (no fraud/low level) and the employee plays hide, it is the only pay-off component and we write $\mathcal{D}^E \equiv v$. Given $s_5 =$ (no fraud/high level/hide), the employee receives her salary v but additionally suffers from high level audit costs k as the manager's team partakes in the provision of more detailed data to the auditor, such that $\mathcal{C}^E \equiv v-k$. If she hides the fraud and the manager and auditor are such that $s_3 =$ (fraud/low level/hide) applies, the employee gains v as well as an indirect benefit m since fraudulent behaviour is not detected. This m arises as the unrevealed fraud of the manager may render the manager's department more profitable from the board's perspective leading to e.g. an annually premium for the employee. The respective employee's pay-off, then, is $\mathcal{B}^E \equiv v+m$. In the last tuple including the employee's choice to hide, i.e. the strategy tuple $s_1 =$ (fraud/high level/hide), she gains her salary v minus the audit costs k. Also, if the thorough audit reveals the fraud, the employee's indirect benefit disappears, such that in s_1, m only arises if the fraud is not detected. This leads to the according employee's pay-off $\mathcal{A}^E \equiv v+(1-p_r)\cdot m-k$.

Next, consider the strategy tuples $s_2 =$ (fraud/high level/disclose) and $s_4 =$ (fraud/low level/ disclose). In case of the latter, we have to take account that a whistle-blower is prone to be dismissed by the manager and thereby experiences a pay-off loss ℓ_s (Moberly 2012). The according exogenous probability of the manager to identify the whistle-blower and to dismiss her is denoted by $\mu \in [0,1]$. The expected loss from being dismissed, therefore, amounts to $\mu \cdot \ell_s$. However, Dyck et al. (2010) point out that a dismissed whistle-blower will not have a similar contract in a future occupation as a different company may not be willing to hire a "traitor" subject to the same payment as granted by the former employer. This is captured by the long-term loss of being fired $\mu \cdot \ell_l$. Additional costs of blowing the whistle and being dismissed may arise in terms of the employee's need to hire a lawyer in a legal dispute with the former employer, i.e. $\mu \cdot c_{LA}$, if the dismissal is illegitimate. We summarize these probable costs of being dismissed by $\mu \cdot c_\mu \equiv \mu \cdot (\ell_s + \ell_l + c_{LA})$. Next to these possible costs, the employee may also experiences some sort of protection by the state in terms of the subsidy b_μ for being dismissed as a result of blowing the whistle (Wolfe et al. 2014). Additionally, there is the exogenous chance that the board may reward the employee for blowing the whistle and sharing her information with the internal auditor (Miceli et al. 2009).[3] Let this probable reward be denoted by b_b. If the employee is not dismissed, she receives her basic salary v.

Whether or not the whistle-blower is dismissed, there also may be social costs associated with whistle-blowing denoted by c_s (Crook 2000). To identify—by no means exhaustive—examples of components thereof, we consider, on the one hand, that the identity of the whistle-blower may become transparent to other colleagues within the same company, who constitute (part of) the social network of the employee. Hence, if she blows the whistle, other colleagues may confront the employee with social exclusion exerted not only by the colleagues themselves, but also by their families. Examples for it are e.g. that personal contact is avoided as others do not want to be involved in the conflict or bullying between children. On the other hand, c_s captures that the identity of the whistle-blower may become transparent to the press although internal whistle-blowing is meant to preserve her identity. This leak may entail high private costs in terms of psychological stress, further financial liabilities and personal despair, see the case of Jesselyn Radack addressed in the introduction. The employee's pay-off conditional upon $s_4 =$ (fraud/low level/disclose) is, then, given by $\mathcal{B}_d^E \equiv (1-\mu) \cdot v^g + \mu \cdot b_\mu^n - c_s$, where $v^g \equiv v + b_b$ can be understood as the gross income of the employee in case of not losing her job and $b_\mu^n \equiv b_\mu - c_\mu$ represents the national subsidy in case of whistle-blowing and being dismissed net of corresponding costs. With regard to the strategy tuple $s_2 =$ (fraud/high level/disclose), we assume that the employee's pay-off involves the same components as in case of s_3 but with high level audit costs k, i.e. $\mathcal{A}_d^E \equiv \mathcal{B}_d^E - k$. In total, the expected pay-off of the employee, $\hat{\pi}^E$, reads

$$\begin{aligned}\hat{\pi}^E = \hat{p}_f \cdot \left[(1-\hat{p}_d) \cdot \left(\hat{p}_h \cdot \mathcal{A}^E + (1-\hat{p}_h) \cdot \mathcal{B}^E\right) + \hat{p}_d \cdot \left(\hat{p}_h \cdot \mathcal{A}_d^E + (1-\hat{p}_h) \cdot \mathcal{B}_d^E\right)\right] \\ + (1-\hat{p}_f) \cdot \left[\hat{p}_h \cdot \mathcal{C}^E + (1-\hat{p}_h) \cdot \mathcal{D}^E\right].\end{aligned} \tag{35}$$

In the present section, the three players simultaneously maximise their individual expected pay-offs taken as given the strategy choices of the other players. Since the formal representation of the expected pay-offs of the manager and auditor here is the same as in the previous section and as we intend to keep the notation consistent, we

[3] As before, we assume that anonymity of the employee is guaranteed with the internal auditor being the one to transfer the reward from the board to the whistle-blower.

reformulate their expected pay-offs by means of assigning a hat to the relevant quantities in (23) and (26). This leads to

$$\hat{\pi}^M = \hat{p}_f \cdot \left[\hat{p}_h \cdot \left((1-\hat{p}_d) \cdot \mathcal{A}^M + \hat{p}_d \cdot \mathcal{A}_d^M\right) + (1-\hat{p}_h) \cdot \left((1-\hat{p}_d) \cdot \mathcal{B}^M + \hat{p}_d \cdot \mathcal{B}_d^M\right)\right] \\ + (1-\hat{p}_f) \cdot \left[\hat{p}_h \cdot \mathcal{C}^M + (1-\hat{p}_h) \cdot \mathcal{D}^M\right] \tag{36}$$

as well as

$$\hat{\pi}^A = \hat{p}_f \cdot \left[\hat{p}_h \cdot \left((1-\hat{p}_d) \cdot \mathcal{A}^A + \hat{p}_d \cdot \mathcal{A}_d^A\right) + (1-\hat{p}_h) \cdot \left((1-\hat{p}_d) \cdot \mathcal{B}^A + \hat{p}_d \cdot \mathcal{B}_d^A\right)\right] \\ +(1-\hat{p}_f) \cdot \left[\hat{p}_h \cdot \mathcal{C}^A + (1-\hat{p}_h) \cdot \mathcal{D}^A\right]. \tag{37}$$

To address the optimization problem in the extended inspection game, let

$$X \equiv (\Delta - \rho^-) \cdot (\mu \cdot (v^g - b_\mu^n) + m + c_s - b_b) - m \cdot (\Gamma - \rho^-), \tag{38}$$

$$Y \equiv p_r \cdot (\Delta - \rho^-) \cdot (\mu \cdot (v^g - b_\mu^n) + c_s - b_b) - \kappa \cdot (\mu \cdot (v^g - b_\mu^n) + m + c_s - b_b), \tag{39}$$

$$Z \equiv \kappa \cdot (\mu \cdot (v^g - b_\mu^n) + m + c_s - b_b) - p_r \cdot m \cdot (\Gamma - \Delta) \tag{40}$$

and solve

$$\max_{\hat{p}_f} \ \hat{\pi}^M, \quad \max_{\hat{p}_h} \ \hat{\pi}^A, \quad \max_{\hat{p}_d} \ \hat{\pi}^E$$

subject to

$$\mu \cdot (v + c_\mu) + (1-p_r) \cdot m + c_s < \mu \cdot b_\mu + (1-\mu) \cdot b_b < \mu \cdot (v + c_\mu) + m + c_s, \tag{41}$$

$$z > 1 - \frac{K}{R^+}, \tag{42}$$

$$\Gamma - \Delta < \frac{\kappa \cdot (\mu \cdot (v^g - b_\mu^n) + m + c_s - b_b)}{p_r \cdot m}, \tag{43}$$

$$\frac{X}{Z} > \frac{p_r \cdot (R^+ + R^-) - K}{p_r((1-z) \cdot R^+ - K)}, \tag{44}$$

$$\Delta < \ \rho^- + \frac{m}{\mu \cdot (v^g - b_\mu^n) + m + c_s - b_b} \cdot (\Gamma - \rho^-) \equiv \bar{\Delta}, \tag{45}$$

$$\Delta > \rho^- + \frac{m}{\mu \cdot (v^g - b^n_\mu) + m + c_s - b_b} \cdot (\Gamma - \rho^-) + \frac{p_r \cdot (R^+ + R^-) - K}{p_r \cdot ((1-z) \cdot R^+ - K)} \cdot \left(\kappa - \frac{p_r \cdot m \cdot (\Gamma - \Delta)}{\mu \cdot (v^g - b^n_\mu) + m + c_s - b_b} \right) \equiv \underline{\Delta}, \tag{46}$$

$$\Delta \in \left(\max\{\rho^-, \underline{\Delta}\}, \bar{\Delta} \right), \tag{47}$$

where the side conditions (41) to (47) ensure that, on the one hand, there is no Nash equilibrium in pure strategies, see the Appendix, and, on the other hand, that the Nash equilibrium probabilities

$$\hat{p}^*_h = \frac{\mu \cdot (v^g - b^n_\mu) + m + c_s - b_b}{p_r \cdot m}, \tag{48}$$

$$\hat{p}^*_d = \frac{p_r \cdot X}{Y}, \tag{49}$$

$$\hat{p}^*_f = \frac{-K \cdot Z}{p_r[((1-z) \cdot R^+ - K) \cdot X - (R^+ + R^-) \cdot Z]} \tag{50}$$

satisfy $\hat{p}^*_h, \hat{p}^*_d, \hat{p}^*_f \in (0, 1)$, see the Appendix.

It is interesting to see that the auditor's probability of choosing high level auditing depends only on pay-off components of the employee, whereas without whistle-blowing, it grounds on those of the manager, exclusively, see (17). The reason is that in the optimization process given endogenous whistle-blowing, the first-order condition for maximising the employee's expected pay-off from (35) with respect to the disclosure probability determines the equilibrium probability of high level auditing of the auditor. Without whistle-blowing, in turn, the latter is determined via the first-order condition for maximising the manager's expected pay-off from (12) with respect to the probability of fraudulent behaviour. Hence, increasing the number of endogenous quantities changes the conditional equation vis-á-vis the probability of high level auditing.

Second, by comparing the manager's equilibrium probability in the benchmark inspection game, see (18), and in case of endogenous whistle-blowing, see (50), we find that only in the latter scenario, the manager's decision depends on the pay-off components of all players including herself. This is the consequence of transforming the benchmark inspection game to a three-person game with simultaneous strategy choices of all players.

Third, it can be seen from (49) that the employee's disclosure decision only depends on the pay-off components associated with the manager and herself. This illustrates the interrelation between whistle-blowing and fraudulent behaviour. That is, the decision of the manager and employee are capable of imposing costs on the respective other player. The auditor, in turn, may only benefit from whistle-blowing whereas the employee gains neither a benefit nor a loss from the auditor's action. Hence, pay-off components of the latter are irrelevant for the employee's decision.

Fourth, to better understand the influence of the parameters on the Nash equilibrium in mixed strategies described by (48) to (50), we again conduct a comparative static analysis. Especially with respect to $\tilde{p}_f^*$ we focus on results that deviate from those discussed in the comparative static analyses in Sects. 2 and 3, as the qualitative results from (20) and (34) (b) carry over to the present scenario. Recall $v^g \equiv v + b_b$ and $b_\mu^n \equiv b_\mu - c_\mu$ to obtain[4]

$$\begin{aligned}&\text{(a): } \frac{\partial \hat{p}_h^*}{\partial m}, \frac{\partial \hat{p}_h^*}{\partial v}, \frac{\partial \hat{p}_h^*}{\partial c_s} > 0, \qquad \text{(b): } \frac{\partial \hat{p}_h^*}{\partial b_b}, \frac{\partial \hat{p}_h^*}{\partial b_\mu^n} < 0,\\ &\text{(c): } \frac{\partial \hat{p}_h^*}{\partial \mu} \begin{Bmatrix} > \\ < \end{Bmatrix} 0 \text{ if } v^g + c_\mu \begin{Bmatrix} > \\ < \end{Bmatrix} b_\mu\end{aligned} \tag{51}$$

and

$$\begin{aligned}&\text{(a): } \frac{\partial \hat{p}_d^*}{\partial m}, \frac{\partial \hat{p}_d^*}{\partial v}, \frac{\partial \hat{p}_d^*}{\partial c_s} < 0, \qquad \text{(b): } \frac{\partial \hat{p}_d^*}{\partial b_b}, \frac{\partial \hat{p}_d^*}{\partial b_\mu^n} > 0,\\ &\text{(c): } \frac{\partial \hat{p}_d^*}{\partial \mu} \begin{Bmatrix} > \\ < \end{Bmatrix} 0 \text{ if } v^g + c_\mu \begin{Bmatrix} < \\ > \end{Bmatrix} b_\mu,\\ &\text{(d): } \frac{\partial \hat{p}_d^*}{\partial \Gamma}, \frac{\partial \hat{p}_d^*}{\partial p_r} > 0, \qquad \text{(e): } \frac{\partial \hat{p}_d^*}{\partial \Delta}, \frac{\partial \hat{p}_d^*}{\partial \rho^-}, \frac{\partial \hat{p}_d^*}{\partial \kappa} < 0\end{aligned} \tag{52}$$

as well as

$$\begin{aligned}&\text{(a): } \frac{\partial \hat{p}_f^*}{\partial m}, \frac{\partial \hat{p}_f^*}{\partial v}, \frac{\partial \hat{p}_f^*}{\partial c_s} < 0, \qquad \text{(b): } \frac{\partial \hat{p}_f^*}{\partial b_b}, \frac{\partial \hat{p}_f^*}{\partial b_\mu^n} > 0,\\ &\text{(c): } \frac{\partial \hat{p}_f^*}{\partial \mu} \begin{Bmatrix} > \\ < \end{Bmatrix} 0 \text{ if } v^g + c_\mu \begin{Bmatrix} < \\ > \end{Bmatrix} b_\mu,\\ &\text{(d): } \frac{\partial \hat{p}_f^*}{\partial \Gamma} > 0, \qquad \text{(e): } \frac{\partial \hat{p}_f^*}{\partial \Delta}, \frac{\partial \hat{p}_f^*}{\partial \rho^-}, \frac{\partial \hat{p}_f^*}{\partial \kappa} < 0.\end{aligned} \tag{53}$$

Consider an increase in the employee's indirect benefit generated by the manager's fraud (m), the employee's salary stemming from her current occupation (v) or the employee's possible social costs of whistle-blowing (c_s). Since a growth in either parameter renders whistle-blowing more costly because of the chance of loosing either money or the job as well as social repercussions, the employee discloses the fraud less likely, see (52) (a). As this ceteris paribus induces the manager to be more willing to act fraudulently, the auditor compensates for less likely whistle-blowing

[4] Complete comparative static results of (48), (49) and (50) are presented in are presented in the Appendix.

by means of raising her efforts via a greater chance of high level auditing, see (51) (a). While the latter effect in isolation reduces the manager's willingness to choose fraud, (53) (a) shows that the increase in the chance of high level auditing outweighs the decrease in the chance of whistle-blowing, such that $\hat{p}_f^*$ shrinks due to the fraud being revealed more likely.

In view of a change in the possible board's reward of a blown whistle (b_b) and the national subsidy for the dismissed whistle-blower net of the costs of the employee accruing from the possible dismissal (b_μ^n), we find from (52) (b) that an increase therein supports the employee and, therefore, raises her willingness to blow the whistle. The auditor anticipates this and, due to substitutionality, reduces her willingness to apply high level auditing, see (51) (b). Note that from the manager's perspective, the latter effect proves to be weaker than the former as (53) (b) connotes that because of the b_b- and b_μ^n-induced smaller chance of high level auditing, there is an upswing in the manager's willingness for fraudulent behaviour.

The influence of the chance of the employee disclosing the fraud to be dismissed by the manager (μ) on the equilibrium probabilities depends on the scale of the national subsidy (b_μ). Suppose that the latter is sufficiently low. (52) (c), then, connotes that an increase in the dismissal probability reduces the employee's willingness to disclose the fraud, as the national support is too low in comparison to the costs arising if the employee loses her job. The μ-induced lower chance of whistle-blowing induces the auditor to apply high level auditing more likely, see (51) (c), because of which the manager's willingness to act fraudulently shrinks, see (53) (c). Given that the national support is sufficiently high, the opposite effects arise mutatis mutandis.

Next, suppose an increase in the manager's benefit from fraudulent behaviour (Γ). Due to a higher net pay-off, this induces the manager to raise her willingness to act fraudulently, see (53) (d). Since the employee is aware thereof and takes into account that the auditor does not react to it, she raises her willingness for whistle-blowing, as well, in order to compensate for the higher risk level, see (52) (d). The opposite effects arise in case of a growth in the manager's costs if her fraud is revealed (Δ), in the long-term reputation loss if her fraud is not revealed (ρ^-) as well as in the manager's costs of high level auditing (κ), see (52) (e) and (53) (e).

The reason why an increase in the detection probability p_r reduces the employee's willingness for whistle-blowing, see (52) (d), is as follows. The employee anticipates that a higher detection probability reduces both the probability for high level auditing and fraudulent behaviour. However, the latter effect turns out to be smaller than the former, such that the employee is inclined to blow the whistle more likely in order to compensate for the more pronounced drop in $\hat{p}_h^*$.

In the terminal step of the analysis of the Nash equilibrium in the present three-person game, we address the influence of endogenous whistle-blowing on the magnitude of the equilibrium probabilities of the manager and auditor to choose fraud and high level auditing, respectively. By contrasting (17), (18), (48) and (50) we find

Proposition 2 *If there is endogenous whistle-blowing,*

(i) *the auditor is less willing to apply high level auditing than in absence of whistle-blowing, i.e.*

$$\hat{p}_h^* < p_h^*.$$

(ii) *the manager is more willing to act fraudulently than in absence of whistle-blowing, i.e.*

$$\hat{p}_f^* > p_f^*.$$

Proof See the Appendix.

As expected, proposition 2 (i) confirms our finding in case of exogenous whistle-blowing as stated in proposition 1 (i) that whistle-blowing serves as a substitute for high level auditing and, therefore, renders the latter less likely. Proposition 2 (ii) furthermore shows that other than in case of exogenous whistle-blowing, the probability of fraudulent behaviour is strictly greater than without. Hence, the impact of less likely high level auditing weighs in so heavily that the risk for the manager of his fraud to be disclosed by the employee is of minor importance.

The driving force for the discrepancy between proposition 1 (ii) and 2 (ii) is as follows. Recall that the games considered in Sects. 3 and 4 can intuitively be distinguished by the fact that the manager and auditor either can influence the decision of the employee (Sect. 4) or cannot (Sect. 3). The comparison of our findings, then, suggests that if the former is the case, the manager takes advantage of the situation by anticipating that the employee may put herself in a worse position by blowing the whistle through corresponding costs than in case of staying quiet. Only if whistle-blowing is costless for the employee (and p_r is sufficiently low), the manager becomes more cautious than without whistle-blowing and takes into account that the employee poses a considerable thread in convicting fraudulent behaviour.

We summarize our findings as follows:

Proposition 3 *In awareness of whistle-blowing*

(i) *the auditor's willingness for high level auditing is lower than in absence of whistle-blowing irrespective of whether or not the manager and auditor can influence the employee's decision.*

(ii) *the manager's willingness to act fraudulently is lower than in absence of whistle-blowing if and only if the manager and auditor can influence the employee's decision and the efficacy of high level auditing without whistle-blowing is sufficiently low.*

5 Conclusion and discussion

This paper addresses the question of whether there is the chance that whistle-blowing can serve as a remedy for fraudulent behaviour. We show that the classical two-person inspection game including a (fraudulent) manager and an (imperfect) internal auditor can be extended by whistle-blowing. Because of the latter, we find that the intensity of the internal audit is generally lower than in absence of whistle-blowing, as the latter serves as a substitute for thorough auditing. Moreover, we find that the chance of whistle-blowing reduces the manager's willingness to act fraudulently as compared to the case without whistle-blowing only if two conditions hold.

First, she must be unable (or cannot) anticipate whether or not blowing the whistle has repercussions on the employee. That is, she takes into account that whistle-blowing can potentially be costless for the employee, which significantly increases the chance of a revelation of her fraud as there might be no reason for the employee to stay quiet. Second, the efficacy of internal audit without whistle-blowing must be sufficiently low, such that whistle-blowing represents a strong improvement relative to the status quo. Otherwise, if one or both conditions are not satisfied, whistle-blowing actually worsens the situations, as, on the one hand, the audit level is lower than without, and, on the other hand, the manager's willingness for fraud grows.

Our results in proposition 3 crucially depend on the degree of the manager and auditor influencing the strategy choice of the whistle-blower. To be precise, we consider two extremes where the manager and auditor are either able or unable to influence the latter. In reality, though, one might assume that not only are there more factors affecting the whistle-blower than assumed, but also that the latter scenario is little realistic. Nonetheless, our inspection game approach with simultaneous strategy choice of all players allows us to present basic interdependencies between and influences of changes in corruptive behaviour of the manager, the audit level of the internal auditor as well as potential whistle-blowing. In future research, our approach can be extended to more than one potential whistle-blower or, respectively, to a repeated game. Additionally, the risk attitude of players should be scrutinised. The focus on a simultaneous two-person game with a manager and an internal auditor can also be extended to a sequential two-stage game, where at the second stage the whistle-blower reacts to the decisions of the manager and auditor made at the first stage.

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Appendix

Comparative static analysis of (31) and (32)

Differentiating (31) with respect to the according parameters while taking account of (1), (2) and (28) provides

$$\frac{\partial \tilde{p}_h^*}{\partial \Gamma} = \frac{1}{p_r \cdot (\Delta - \rho^-) \cdot (1 - p_d)} > 0,$$
$$\frac{\partial \tilde{p}_h^*}{\partial \Delta} = -\frac{\Gamma - \rho^-}{p_r \cdot (\Delta - \rho^-)^2 \cdot (1 - p_d)} < 0,$$
$$\frac{\partial \tilde{p}_h^*}{\partial \rho^-} = \frac{\Gamma - \Delta}{p_r \cdot (\Delta - \rho^-)^2 \cdot (1 - p_d)} < 0,$$
$$\frac{\partial \tilde{p}_h^*}{\partial p_r} = -\frac{\Gamma - \rho^- - (\Delta - \rho^-) \cdot p_d}{p_r^2 \cdot (\Delta - \rho^-) \cdot (1 - p_d)} < 0,$$
$$\frac{\partial \tilde{p}_h^*}{\partial p_d} = \frac{\Gamma - \Delta}{p_r \cdot (\Delta - \rho^-) \cdot (1 - p_d)^2} < 0.$$

Let $M \equiv \big((1 - p_d) \cdot p_r \cdot (R^+ + R^-) + p_d \cdot (1 - z) \cdot R^+\big)^2$. Differentiating (32) with respect to the relevant parameters subject to (16) leads to

$$\frac{\partial \tilde{p}_f^*}{\partial K} = \frac{1}{M} > 0,$$
$$\frac{\partial \tilde{p}_f^*}{\partial R^+} = -\frac{K \cdot \big((1 - p_d) \cdot p_r + p_d \cdot (1 - z)\big)}{M} < 0,$$
$$\frac{\partial \tilde{p}_f^*}{\partial R^-} = -\frac{(1 - p_d) \cdot p_r \cdot K}{M} < 0,$$
$$\frac{\partial \tilde{p}_f^*}{\partial p_r} = -\frac{(1 - p_d) \cdot K \cdot (R^+ + R^-)}{M} < 0,$$
$$\frac{\partial \tilde{p}_f^*}{\partial p_d} = \frac{K \cdot \big(p_r \cdot (R^+ + R^-) - (1 - z) \cdot R^+\big)}{M} \left\{ \begin{matrix} < \\ > \end{matrix} \right\} 0 \text{ if } p_r \left\{ \begin{matrix} < \\ > \end{matrix} \right\} \frac{(1 - z) \cdot R^+}{R^+ + R^-},$$
$$\frac{\partial \tilde{p}_f^*}{\partial z} = \frac{K \cdot R^+}{M} > 0.$$

Proof of proposition 1

To prove proposition 1 (i), exploit (1), (17) and (31) and simplify to obtain

$$p_h^* > \tilde{p}_h^*$$
$$\Leftrightarrow \quad \frac{\Gamma - \rho^-}{p_r \cdot (\Delta - \rho^-)} > \frac{\Gamma - \rho^- - (\Delta - \rho^-) \cdot p_d}{p_r \cdot (\Delta - \rho^-) \cdot (1 - p_d)}$$
$$\Leftrightarrow (1 - p_d) \cdot (\Gamma - \rho^-) > \Gamma - \rho^- - (\Delta - \rho^-) \cdot p_d$$
$$\Leftrightarrow \quad -p_d \cdot (\Gamma - \rho^-) > -(\Delta - \rho^-) \cdot p_d$$
$$\Leftrightarrow \quad \Gamma < \Delta,$$

which is true by (2).

Proposition 1 (ii) is proven by comparing (18) and (32) subject to (16). This leads to

$$
\begin{aligned}
& p_f^* > \tilde{p}_f^* \\
\Leftrightarrow\quad & \frac{K}{p_r \cdot (R^+ + R^-)} > \frac{K}{(1-p_d)\cdot p_r \cdot (R^+ + R^-) + p_d \cdot (1-z) \cdot R^+} \\
\Leftrightarrow\quad & p_r \cdot (R^+ + R^-) < (1-p_d) \cdot p_r \cdot (R^+ + R^-) + p_d \cdot (1-z) \cdot R^+ \\
\Leftrightarrow\quad & p_d \cdot p_r \cdot (R^+ + R^-) < p_d \cdot (1-z) \cdot R^+ \\
\Leftrightarrow\quad & p_r < \frac{(1-z)\cdot R^+}{R^+ + R^-}
\end{aligned}
$$

where due to the general assumption of $z \in (0,1)$, we have $\frac{(1-z)\cdot R^+}{R^+ + R^-} \in (0,1)$. The opposite case of $p_f^* < \tilde{p}_f^*$, consequently, holds if $p_r > \frac{(1-z)\cdot R^+}{R^+ + R^-}$.

Discussion of strategy tuples from Fig. 1 in the three-person inspection game with endogenous whistle-blowing

As each player aims at maximising its own pay-off according to Nash and since we intend to solve the optimisation problem in accordance with an inspection game approach, it is necessary to figure out, if there is a Nash equilibrium in pure strategies in the first place. We successively verify whether or not one of the strategy tuples defined in Fig. 1 results in the highest pay-off for each player subject to the quantities given in Table 2. In particular, we investigate for each player's possible strategy if she has an incentive to change her strategy taking as given the choices of the other players. Recall, that $v^g \equiv v + b_b$.

Strategy tuple s_1 = (fraud/high level/hide):

- The manager prefers no fraud as in s_5 to fraud as in s_1, since $\mathcal{A}^M < \mathcal{C}^M$ by (13).
- The auditor prefers high level as in s_1 to low level as in s_3, since $\mathcal{A}^A > \mathcal{B}^A$ by (15).

$\Rightarrow s_1$ cannot be a Nash equilibrium in pure strategies irrespective of the strategy choice of the employee.

Strategy tuple s_2 = (fraud/high level/disclose):

- There is no alternative for the manager. He, therefore, chooses fraud as in s_2.
- The auditor prefers high level as in s_2 to low level as in s_4, i.e. $s_2 \succ s_4$, and vice versa if

$$s_2 \begin{Bmatrix} \succ \\ \prec \end{Bmatrix} s_4 \quad \Leftrightarrow \quad \mathcal{A}_d^A \begin{Bmatrix} > \\ < \end{Bmatrix} \mathcal{B}_d^A \quad \Leftrightarrow \quad z \begin{Bmatrix} < \\ > \end{Bmatrix} 1 - \frac{K}{R^+}, \tag{54}$$

  where, due to (15), the bound on z from (54) is less than one.
- The employee prefers disclose as in s_2 to hide as in s_1, i.e. $s_2 \succ s_1$, and vice versa, if

$$s_2 \begin{Bmatrix} \succ \\ \prec \end{Bmatrix} s_1 \quad \Leftrightarrow \quad \mathcal{A}_d^E \begin{Bmatrix} > \\ < \end{Bmatrix} \mathcal{A}^E \quad \Leftrightarrow \quad (1-\mu)\cdot b_b + \mu \cdot b_\mu \begin{Bmatrix} > \\ < \end{Bmatrix} \mu \cdot (v + c_\mu) + (1-p_r)\cdot m + c_s \tag{55}$$

  and we conclude

Lemma 1 *Suppose that the manager, auditor and employee simultaneously choose one from their respective two strategies. Then, there exists a Nash equilibrium in the pure strategies (fraud/high level/disclose) if and only if*

$$z < 1 - \frac{K}{R^+},$$
$$(1-\mu)\cdot b_b + \mu \cdot b_\mu > \mu \cdot (v + c_\mu) + (1-p_r)\cdot m + c_s.$$

Given (30), *(fraud/high level/disclose) is not a Nash equilibrium in pure strategies if either*

$$z \in \left(1 - \frac{K}{R^+},\ \min\left\{1,\ 1 + \frac{(1-p_d)\cdot p_r \cdot (R^+ + R^-) - K}{p_d \cdot R^+}\right\}\right) \tag{56}$$

or

$$(1-\mu)\cdot b_b + \mu \cdot b_\mu < \mu \cdot (v + c_\mu) + (1-p_r)\cdot m + c_s$$

or both.

Strategy tuple s_3 = (fraud/low level/hide):

- The manager prefers fraud as in s_3 to no fraud as in s_6, since $\mathcal{B}^M > \mathcal{D}^M$ by (14).
- The auditor prefers high level as in s_1 to low level as in s_2, since $\mathcal{A}^A > \mathcal{B}^A$ by (15).

$\Rightarrow s_3$ cannot be a Nash equilibrium in pure strategies irrespective of the strategy choice of the employee.

Strategy tuple s_4 = (fraud/low level/disclose):

- There is no alternative for the manager. He, therefore, chooses fraud as in s_4.
- The considerations of the auditor read along the line of the strategy tuple s_2, see (54).
- The employee prefers disclose as in s_4 to hide as in s_3, i.e. $s_4 \succ s_3$, and vice versa, if

$$s_4 \begin{Bmatrix} \succ \\ \prec \end{Bmatrix} s_3 \quad \Leftrightarrow \quad \mathcal{B}_d^E \begin{Bmatrix} > \\ < \end{Bmatrix} \mathcal{B}^E \quad \Leftrightarrow \quad (1-\mu)\cdot b_b + \mu \cdot b_\mu \begin{Bmatrix} > \\ < \end{Bmatrix} \mu \cdot (v + c_\mu) + m + c_s \tag{57}$$

and we conclude

Lemma 2 *Suppose that the manager, auditor and employee simultaneously choose one from their respective two strategies. Then, there exists a Nash equilibrium in the pure strategies (fraud/low level/disclose) if and only if*

$$z > 1 - \frac{K}{R^+},$$
$$(1-\mu)\cdot b_b + \mu \cdot b_\mu > \mu \cdot (v + c_\mu) + m + c_s.$$

(fraud/low level/disclose) is not a Nash equilibrium in pure strategies if either

$$z < 1 - \frac{K}{R^+}$$

or

$$(1-\mu)\cdot b_b + \mu \cdot b_\mu < \mu \cdot (v + c_\mu) + m + c_s$$

or both.

Strategy tuple s_5 = (no fraud/high level/hide):

- The manager prefers no fraud as in s_5 to fraud as in s_1, since $\mathcal{A}^M < \mathcal{C}^M$ by (13).
- The auditor prefers low level as in s_6 to high level as in s_5, since $\mathcal{C}^A < \mathcal{D}^A$ by (16).
- The employee has no alternative and chooses hide as in s_5.

$\Rightarrow s_5$ cannot be a Nash equilibrium in pure strategies.

Strategy tuple s_6 = (no fraud/low level/hide):

- The manager prefers fraud as in s_3 to no fraud as in s_6, since $\mathcal{B}^M > \mathcal{D}^M$ by (14).
- The auditor prefers low level as in s_6 to high level as in s_5, since $\mathcal{C}^A < \mathcal{D}^A$ by (16).
- The employee has no alternative and chooses hide as in s_6.

$\Rightarrow s_6$ cannot be a Nash equilibrium in pure strategies.

Discussion of Nash equilibrium probabilities in the three-person inspection game with endogenous whistle-blowing

Recall $v^g \equiv v + b_b$. Notice from (48) that $\hat{p}_h^* \in (0,1)$ requires the probable appropriation of the board b_b and the possible national protection of the whistle-blower b_μ to be such that

$$\mu \cdot (v + c_\mu) + (1 - p_r) \cdot m + c_s < (1 - \mu) \cdot b_b + \mu \cdot b_\mu < \mu \cdot (v + c_\mu) + m + c_s, \tag{58}$$

according to which s_4 will not arise as a Nash equilibrium in pure strategies, see Lemma 2. In order to avoid that s_2 may represent the Nash equilibrium, see Lemma 1, we consider (56) to hold in terms of $z > 1 - \frac{K}{R^+}$.

To check for $\hat{p}_d^*$ from (49) to attain a value between zero and one, be aware that its denominator is negative, see

$$Y < 0$$
$$\Leftrightarrow$$
$$p_r \cdot \underbrace{(\Delta - \rho^-)}_{>0 \text{ by } (1)} \cdot \underbrace{(\mu \cdot (v^g - b_\mu^n) + c_s - b_b)}_{<0 \text{ by } (58)} - \kappa \cdot \underbrace{(\mu \cdot (v^g - b_\mu^n) + m + c_s - b_b)}_{>0 \text{ by } (58)} < 0. \tag{59}$$

The numerator, thus, must be negative as well so that $\hat{p}_d^* > 0$. To guarantee this, recall that the manager's costs in case of her fraud being revealed (Δ) are assumed to exceed her long-term reputation loss if there is only the internal audit and it does not reveal the fraud (ρ^-), see (1). A sufficient condition for a negative numerator is, then, given if Δ is not too high in terms of

$$X < 0 \quad \Leftrightarrow \quad \Delta < \rho^- + \underbrace{\frac{m}{\mu \cdot (v^g - b_\mu^n) + m + c_s - b_b}}_{>1 \text{ due to (58)}} \cdot \underbrace{(\Gamma - \rho^-)}_{>0 \text{ by (14)}} \equiv \bar{\Delta}. \tag{60}$$

For $\hat{p}_d^* < 1$ to hold, we find that Z from (40) must be positive, i.e.

$$Z > 0 \quad \Leftrightarrow \quad \underbrace{\Gamma - \Delta}_{<0 \text{ by (2)}} < \underbrace{\frac{\kappa \cdot (\mu \cdot (v^g - b_\mu^n) + m + c_s - b_b)}{p_r \cdot m}}_{>0 \text{ by (58)}}. \tag{61}$$

Since the left-hand side is negative while the right-hand side is positive, $Z > 0$ applies and $\hat{p}_d^* \in (0, 1)$ follows from (60).

Closer inspection of (50) shows that the numerator of $\hat{p}_f^*$ is negative because of (16) and $Z > 0$. Hence, in order for $\hat{p}_f^* > 0$ to hold, the denominator must be negative as well. Since we generally have

$$\underbrace{((1 - z) \cdot R^+ - K)}_{<0 \text{ since } z > 1 - \frac{K}{R^+} \text{ by (56)}} \cdot \underbrace{X}_{<0 \text{ by (60)}} - \underbrace{(R^+ + R^-)}_{>0 \text{ by (15)}} \cdot \underbrace{Z}_{>0 \text{ by (61)}} \gtrless 0,$$

it turns out that a sufficient condition for a negative denominator in (50) is

$$\frac{X}{Z} > \frac{R^+ + R^-}{(1 - z) \cdot R^+ - K}. \tag{62}$$

Moreover, $\hat{p}_f^* < 1$ requires that

$$\frac{X}{Z} > \frac{p_r \cdot (R^+ + R^-) - K}{p_r((1 - z) \cdot R^+ - K).} \tag{63}$$

As the lower bound on X/Z from (63) is less negative than that in (62), we obtain $\hat{p}_f^* \in (0, 1)$ subject to (63), which is equivalent to

$$\Delta > \rho^- + \frac{m}{\mu \cdot (v^g - b_\mu^n) + m + c_s - b_b} \cdot (\Gamma - \rho^-) + \frac{p_r \cdot (R^+ + R^-) - K}{p_r \cdot ((1-z) \cdot R^+ - K)} \cdot \left(k - \frac{p_r \cdot m \cdot (\Gamma - \Delta)}{\mu \cdot (v^g - b_\mu^n) + m + c_s - b_b} \right) \equiv \underline{\Delta}. \tag{64}$$

Notice that $\underline{\Delta}$ from (64) is smaller than $\bar{\Delta}$ from (60) as the third addend of the former is negative. It is, however, unclear whether or not $\underline{\Delta}$ is in line with (1) via $\underline{\Delta} > \rho^-$. A feasible domain for Δ subject to (1) is, therefore, given by $\Delta \in \left(\max\{\rho^-, \underline{\Delta}\}, \bar{\Delta}\right)$.

Comparative static analysis of (48), (49) and (50)

Recall $v^g \equiv v + b_b$ and $b^n_\mu \equiv b_\mu - c_\mu$. Differentiating (48) with respect to the relevant parameters while taking account of (58) gives

$$\frac{\partial \hat{p}^*_h}{\partial m} = -\frac{\mu \cdot (v^g - b^n_\mu) + c_s - b_b}{p_r \cdot m^2} > 0,$$
$$\frac{\partial \hat{p}^*_h}{\partial v} = -\frac{\partial \hat{p}^*_h}{\partial b^n_\mu} = \frac{\mu}{p_r \cdot m} > 0,$$
$$\frac{\partial \hat{p}^*_h}{\partial b_b} = -\frac{1-\mu}{p_r \cdot m} < 0,$$
$$\frac{\partial \hat{p}^*_h}{\partial c_s} = \frac{1}{p_r \cdot m} > 0,$$
$$\frac{\partial \hat{p}^*_h}{\partial p_r} = -\frac{\mu \cdot (v^g - b^n_\mu) + m + c_s - b_b}{p_r^2 \cdot m} < 0,$$
$$\frac{\partial \hat{p}^*_h}{\partial \mu} = \frac{v^g - b^n_\mu}{p_r \cdot m} \begin{Bmatrix} > \\ < \end{Bmatrix} 0 \text{ if } v^g + c_\mu \begin{Bmatrix} > \\ < \end{Bmatrix} b_\mu.$$

Differentiating (49) with respect to the relevant parameters subject to (1), (2), (14), (58), X from (38) with $X < 0$, see (60), Y from (39) with $Y < 0$, see (59), leads to

$$\frac{\partial \hat{p}^*_d}{\partial \Gamma} = -\frac{p_r \cdot m}{Y} > 0,$$
$$\frac{\partial \hat{p}^*_d}{\partial p_r} = -\frac{X \cdot \kappa \cdot (\mu \cdot (v^g - b^n_\mu) + m + c_s - b_b)}{Y^2} > 0,$$
$$\frac{\partial \hat{p}^*_d}{\partial \Delta} = \frac{p_r \cdot \left(m \cdot (\Gamma - \rho^-) \cdot p_r \cdot (\mu \cdot (v^g - b^n_\mu) + c_s - b_b) - \kappa \cdot (\mu \cdot (v^g - b^n_\mu) + m + c_s - b_b)\right)}{Y^2} < 0,$$
$$\frac{\partial \hat{p}^*_d}{\partial \rho^-} = \frac{p_r \cdot (\mu \cdot (v^g - b^n_\mu) + c_s - b_b) \cdot \left(m \cdot p_r \cdot (\Delta - \Gamma) + \kappa \cdot (\mu \cdot (v^g - b^n_\mu) + m + c_s - b_b)\right)}{Y^2} < 0,$$
$$\frac{\partial \hat{p}^*_d}{\partial \kappa} = \frac{p_r \cdot X \cdot (\mu \cdot (v^g - b^n_\mu) + m + c_s - b_b)}{Y^2} < 0,$$
$$\frac{\partial \hat{p}^*_d}{\partial v} = -\frac{\partial \hat{p}^*_d}{\partial b^n_\mu} = -\frac{p_r \cdot m \cdot \mu \cdot \left(p_r \cdot (\Delta - \rho^-) \cdot (\Delta - \Gamma) + \kappa \cdot (\Gamma - \rho^-)\right)}{Y^2} < 0,$$
$$\frac{\partial \hat{p}^*_d}{\partial b_b} = \frac{p_r \cdot (1-\mu) \cdot m \cdot \left(p_r \cdot (\Delta - \rho^-) \cdot (\Delta - \Gamma) + \kappa \cdot (\Gamma - \rho^-)\right)}{Y^2} > 0,$$
$$\frac{\partial \hat{p}^*_d}{\partial c_s} = -\frac{p_r \cdot m \cdot \left(p_r \cdot (\Delta - \rho^-) \cdot (\Delta - \Gamma) + \kappa \cdot (\Gamma - \rho^-)\right)}{Y^2} < 0,$$
$$\frac{\partial \hat{p}^*_d}{\partial \mu} = -\frac{p_r \cdot m \cdot (v^g - b^n_\mu) \cdot \left(p_r \cdot (\Delta - \rho^-) \cdot (\Delta - \Gamma) + \kappa \cdot (\Gamma - \rho^-)\right)}{Y^2} \begin{Bmatrix} < \\ > \end{Bmatrix} 0 \text{ if } v^g + c_\mu \begin{Bmatrix} > \\ < \end{Bmatrix} b_\mu,$$
$$\frac{\partial \hat{p}^*_d}{\partial m} = \frac{p_r \cdot ((\Delta - \Gamma) \cdot Y + X \cdot \kappa)}{Y^2} < 0.$$

Let $W \equiv \big((1-z)\cdot R^+ - K\big)\cdot X - (R^+ + R^-)\cdot Z$ with $W<0$ because of (62). Differentiating (50) with respect to the relevant parameters while exploiting (1), (2), (15), (16), $z > 1 - \frac{K}{R^+}$ from (56), (58), X from (38) with $X<0$, see (60), Z from (40) with $Z>0$, see (61), yields

$$
\begin{aligned}
\frac{\partial \hat{p}_f^*}{\partial K} &= \frac{-Z\cdot W - K\cdot Z\cdot X}{p_r\cdot W^2} > 0,\\
\frac{\partial \hat{p}_f^*}{\partial z} &= -\frac{K\cdot Z\cdot R^+\cdot X}{p_r\cdot W^2} > 0,\\
\frac{\partial \hat{p}_f^*}{\partial R^+} &= \frac{K\cdot Z\cdot((1-z)\cdot X - Z)}{p_r\cdot W^2} < 0,\\
\frac{\partial \hat{p}_f^*}{\partial R^-} &= -\frac{K\cdot Z^2}{p_r\cdot W^2} < 0,\\
\frac{\partial \hat{p}_f^*}{\partial p_r} &= \frac{K\cdot m\cdot(\Gamma-\Delta)\cdot((1-z)\cdot R^+ - K)\cdot X}{p_r\cdot W^2} < 0,\\
\frac{\partial \hat{p}_f^*}{\partial \Gamma} &= -\frac{K\cdot m\cdot((1-z)\cdot R^+ - K)\cdot(Z - p_r\cdot X)}{p_r\cdot W^2} > 0,\\
\frac{\partial \hat{p}_f^*}{\partial \Delta} &= -\frac{K\cdot((1-z)\cdot R^+ - K)\cdot\Big(p_r\cdot m\cdot X - Z\cdot(\mu\cdot(v^g - b_\mu^n) + m + c_s - b_b)\Big)}{p_r\cdot W^2} < 0,\\
\frac{\partial \hat{p}_f^*}{\partial \rho^-} &= -\frac{K\cdot Z\cdot((1-z)\cdot R^+ - K)\cdot(\mu\cdot(v^g - b_\mu^n) + c_s - b_b)}{p_r\cdot W^2} < 0,\\
\frac{\partial \hat{p}_f^*}{\partial \kappa} &= -\frac{K\cdot((1-z)\cdot R^+ - K)\cdot(\mu\cdot(v^g - b_\mu^n) + m + c_s - b_b)\cdot X}{p_r\cdot W^2} < 0,\\
\frac{\partial \hat{p}_f^*}{\partial v} &= -\frac{\partial \hat{p}_f^*}{\partial b_\mu^n} = -\frac{K\cdot\mu\cdot((1-z)\cdot R^+ - K)\cdot(\kappa\cdot X - Z\cdot(\Delta-\rho^-))}{p_r\cdot W^2} < 0,\\
\frac{\partial \hat{p}_f^*}{\partial c_s} &= -\frac{K\cdot((1-z)\cdot R^+ - K)\cdot(\kappa\cdot X - Z\cdot(\Delta-\rho^-))}{p_r\cdot W^2} < 0,\\
\frac{\partial \hat{p}_f^*}{\partial b_b} &= \frac{K\cdot(1-\mu)\cdot\big((1-z)\cdot R^+ - K\big)\cdot(\kappa\cdot X - Z\cdot(\Delta-\rho^-))}{p_r\cdot W^2} > 0,\\
\frac{\partial \hat{p}_f^*}{\partial \mu} &= -\frac{K\cdot(v^g - b_\mu^n)\cdot((1-z)\cdot R^+ - K)\cdot(\kappa\cdot X - Z\cdot(\Delta-\rho^-))}{p_r\cdot W^2} \begin{Bmatrix} < \\ > \end{Bmatrix} 0 \text{ if } v^g + c_\mu \begin{Bmatrix} > \\ < \end{Bmatrix} b_\mu,\\
\frac{\partial \hat{p}_f^*}{\partial m} &= -\frac{K\cdot((1-z)\cdot R^+ - K)\cdot\big(Z\cdot(\Gamma-\Delta) + (\kappa + p_r\cdot(\Delta-\Gamma))\cdot X\big)}{p_r\cdot W^2} < 0.
\end{aligned}
$$

Proof of proposition 2

To prove proposition 2 (i), compare (17) and (48). Taking account of (1) and (58) results in

$$\begin{aligned} &\hat{p}_h^* < p_h^* \\ &\Leftrightarrow \frac{\mu\cdot v+m+c-(1-\mu)\cdot b_b-\mu\cdot b_s}{p_r\cdot m} < \frac{\Gamma-\rho^-}{p_r\cdot(\Delta-\rho^-)} \\ &\Leftrightarrow \Delta < \rho^- + \frac{m}{\mu\cdot v+m+c-(1-\mu)\cdot b_b-\mu\cdot b_s}\cdot(\Gamma-\rho^-), \end{aligned} \tag{65}$$

which is true by (60).

We prove proposition 2 (ii) by comparing (18) and (50) conditional upon (15), the assumption of $z > 1 - \frac{K}{R^+}$ from (56), $X < 0$ from (60) and (62). We obtain

$$\begin{aligned} &\hat{p}_f^* > p_f^* \\ \Leftrightarrow\quad & \frac{-K\cdot Z}{p_r\cdot[((1-z)\cdot R^+-K)\cdot X-(R^++R^-)\cdot Z]} > \frac{K}{p_r\cdot(R^++R^-)} \\ \Leftrightarrow\quad & -Z\cdot(R^++R^-) < ((1-z)\cdot R^+-K)\cdot X-(R^++R^-)\cdot Z \\ \Leftrightarrow\quad & 0 < ((1-z)\cdot R^+-K)\cdot X, \end{aligned}$$

which is true.

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