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# Organization and Incentivization of Risk Management

**Dissertation**

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## List of Abbreviations

| | |
|---|---|
| BU | business unit |
| BUM | business unit manager |
| CEO | Chief Executive Officer |
| CFO | Chief Financial Officer |
| COSO | Committee of Sponsoring Organizations of the Treadway Commission |
| CRO | Chief Risk Officer |
| DIN | Deutsches Institut für Normung |
| ERM | enterprise risk management |
| FSA | Financial Services Authority |
| ISO | International Organization for Standardization |
| LEN | linear exponential normal |
| OECD | Organisation for Economic Co-operation and Development |
| PM | performance measure |
| RM | risk manager |
| RMS | risk management system |
| UNECE | United Nations Economic Commission for Europe |

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# 1 Introduction

## 1.1 Motivation and objectives

Risk management is defined as “coordinated activities to direct and control an organization with regard to risk” (DIN e. V. 2018, 3.2). The asymmetrical approach to risk focuses on downside risk, recognized as potential adverse effects (Haimes 2009). However, in risk management frameworks, a symmetrical approach prevails, with risk seen as a threat and an opportunity (Simkins and Ramirez 2008; Siegel 2018; Lemos 2020) and defined as “effect of uncertainty on objectives” and “deviation from the expected” (DIN e. V. 2018, 3.1). Most firms implement some form of risk management and view it as necessary from an organizational point of view (Fraser and Simkins 2016; Siegel 2018). However, there is no universal way to optimally deal with risk, as the designated risk level depends on owners’ individual risk appetite and aims, given the general truth that higher profits necessarily incur higher risks (Arena et al. 2010; UNECE 2012).

As part of management, risk management develops structures for discussion about the future, enhances rationality of operational and strategic choices, and the information structure (UNECE 2012). Furthermore, risk management can be perceived as a strategic resource, with firms implementing it to adhere to best practices in the industry and remain competitive (Karanja 2017). Empirical studies report a positive relationship between the adoption of risk management and a firm’s value (Smithson and Simkins 2005; Hoyt and Liebenberg 2011), as well as a decrease in the volatility of earnings and stock prices (Pagach and Warr 2010; Bromiley et al. 2015; Karanja 2017). The presence of risk management enhances the firm’s functioning (Simkins and Ramirez 2008) and is characteristic of resilient organizations that run their business efficiently in constantly changing environments (Siegel 2018). As firms still tend to underestimate the role of risk management for financial success, especially concerning the costs they must carry if risk management fails (OECD 2014), its relevance is accounted for by diverse regulatory bodies. It is subject to many standards and regulations, including but not limited to Basel III, the Sarbanes-Oxley Act, the COSO framework, and standard norm for the implementation of risk management principles ISO 31000:2018, which has been applied worldwide since its publication (UNECE 2012).

As the board’s responsibility and key function, risk management cannot be separated from management as a whole (Gordon et al. 2009; OECD 2014). The board should be able to understand and specify the degree of risk that a firm faces and organize its management through the assignment of responsibility and accountability (Simkins and Ramirez 2008; OECD 2014).

To this end, companies delegate risk management to line managers (OECD 2014) in the form of a decentralized structure. Alternatively or parallelly, a centralized organizational design with a risk manager (RM) in a staff position within a managerial team is possible (Reavis 1969). The organizational structure remains pertinent, as the positive relation between implementation of risk management and firm performance may depend on its "right" design given such factors as environmental uncertainty, size of the firm, internal interdependencies between units, and external regulations and laws (Gordon et al. 2009). As risks become more versatile, the demand for risk management from regulatory bodies increases (Sekerci and Pagach 2020). At the national level, stock-listed firms are often legally required to organize risk management. It is also a part of corporate governance for small- and medium-sized businesses. The general design depends on whether risk management is obligatory or occurs on a comply-or-explain basis (UNECE 2012; OECD 2014). A survey of 27 OECD countries concerning the design of risk management as demanded by law, regulation, or code accounted for only three countries without any regulation on risk management design. In other cases, different organizational designs were required to be implemented parallelly, revealing 17 countries in which the board was responsible for risk management, 21 countries in which board-level committees were required, 21 countries with internal risk management systems (RMSs), and finally four countries with the recommended appointment of a Chief Risk Officer (CRO) (OECD 2014).

Within different organizational structures, the identity of an RM can be assigned to different actors: CROs, internal auditors, risk management specialists, management accountants (Arena et al. 2010), or Chief Financial Officers (CFOs) (Bodnar et al. 2019). RMs assume the role of advisory to managers or boards (Arena et al. 2010), rather than simple risk calculators or insurers of the past (Reavis 1969). The RM's activity is focused not on increasing the profits themselves, but on managing the risk in a way optimal for the firm's specifics. The commitment to risk management as a task is connected to the characteristics of the person carrying it out and their position within the hierarchy. Interdependencies between managers and their units may influence individual motivation (Arena et al. 2010). Personal risk aversion also impacts RM's engagement in delegated tasks, with empirically mixed results with regard to firm's profit, dependent on the other environmental variables (Tufano 1996; Hoitash et al. 2016; Bodnar et al. 2019). Amidst these influences, the compensation contract for an RM, entailing risk management as a task, is indispensable (Fraser and Simkins 2016). The optimal design of an incentive contract may be determined by a multitude of factors, such as personal characteristics (e.g., risk aversion, effort aversion, altruism, or envy of an individual) and organizational aspects (e.g., hierarchical placement of the manager, grade of centralization of the firm and its size). Empirical research shows that incentives for top management depend on their roles within firms, with Chief Executive Officers (CEOs) and oversight managers responsible for the whole firm earning more than business unit managers (BUMs). Erroneous incentive pay is believed to induce excessive risk-taking and to lead to financial crises, which in the UK induced changes in remuneration policy through the implementation of the United Kingdom Remuneration Code (Kleymenova and Tuna 2021). It demands compensation policies consistent with "effective risk management", but without providing concrete recommendations (FSA 2009).

An assessment basis for contractual incentives is usually one or multiple performance measures (PMs). For evaluating CEOs, firm performance is often used (Lewellen and Huntsman 1970; Aggarwal and Samwick 2003). Compensating the executives on equity tends to align the risk of the manager and firm (Bodnar et al. 2019) and enhance the firm's performance (Sanders 1999). From the empirical research on the compensation of RMs, if they own more stock (more options), more (less) risk management is observed (Tufano 1996). Similarly, when their portfolios are more sensitive to a firm's stock price, more risk management occurs (Knopf et al. 2002). Thus, there is a connection between the risk the RMs face due to PMs used in their compensation contracts and their risk management decisions, which also influences the firm's performance.

Overall, the organization of risk management and incentive contracts for managers carrying it out emerge as crucial for success. Moreover, efficient risk management is relevant for the stability of the economy as a whole, and thus important from the perspective of regulatory bodies. The literature so far remains vague on the explicit recommendations, rather presenting the existing practices than evaluating them in a founded manner (Arena et al. 2010; Bennett 2017; Bodnar et al. 2019; Kleymenova and Tuna 2021). Neither the analytical nor the empirical organizational literature discusses the RMs in their distinct roles apart from other managers, even though their special quality seems evident. Due to these omissions, the central problems regarding the organization and incentivization of risk management are only discussed rudimentarily in the literature. To close this gap, which will benefit firms in general and a science-based policy, further research is necessary.

Thus, three interconnected areas emerge in need of addressing:

1. **Organization of risk management within firms,** analyzing the number and placement of RMs within the hierarchical structure of the firm, thus discussing the grade of centralization of risk management, as well as the optimal firm and team size in this context.
2. **Optimal incentives for RMs,** analyzing the influence of RMs' traits and environmental factors on incentive design.
3. **Measuring the RMs' performance,** analyzing the number and characteristics of PMs used in contracts, and the interdependencies between them.

Empirical research is often implemented to explain the effects of existing or newly introduced solutions, enabling certain suggestions for the practice. However, for stylized recommendations, analytical research seems to be a more suitable tool. It allows for the construction of simplified models, stringently depicting available solutions, without risking the disrupting effects of multiple environmental factors. Such models represent the whole firm or single BUs in a formalized manner, accounting for the actors within them. These individuals are reduced to a few core characteristics, overall providing more clarity about the processes within firms. One branch of analytical research is the agency theory, especially focused on the normative questions of entrepreneurial organization and incentivization. The results obtained in this manner can be then used as a basis for hypotheses in further empirical research.

Agency theory is thus a methodological tool of choice in this thesis. Originated by Arrow (1963) on contractual relationships in the context of insurance, it was developed by Jensen and Meckling (1976) and incorporated into the theory of a firm as a complex net of contractual relationships. Since then, various problems have been discussed within agency theoretical research. An analysis of the optimal structure of incentives (Mirrlees 1976, and many others) shows that contractual payment occurs only when a certain performance has been observed. This observation may occur directly through supervision, which is the focus of Calvo and Wellisz (1978) and many others, providing insights into the hierarchical organization of firms, loss of control, and limit to firm size. The alternate possibility of observing a performance occurs in the form of PMs, which are used in contracts, and characterized by sensitivity, precision, and congruence, as studied by Demski (1976), Baker (1992), and Banker and Datar (1989), among others. Contracting under moral hazard with imperfect information, as analyzed by Harris and Raviv (1979), Holmström (1979), and several others, points toward the relevance of any additional information, however imperfect, for incentive contracts.

This shortlist of topics from agency theoretical literature is by no means complete. With such a vast body of studies, it could be presumed that some questions pertaining to risk management have already been answered. To this end, risk management must first be incorporated into the framework of the agency theory. Generally, risks are variances in financial results (Arena et al. 2010), making risk management a variance-reducing activity. The other variance-reducing activity that can be found in agency literature is monitoring, concentrating on decreasing the variance of PMs (increasing their precision) (e.g. Liang et al. 2008). However, the focus of risk management is on the overall risk of a firm, not on the risks of individual PMs. Hence, the relationship between monitoring and risk management requires closer examination. The insights into managerial incentivization and organization of the firm, originating from previous research on agency theory, cannot be implemented in the context of risk management without further review and critique.

| **Research Question**<br>How should the firms optimally organize and incentivize risk management and what effects do the different solutions have? | | |
|---|---|---|
| **Literature Review** | **Formal-Analytical Study** | **Simulation Study** |
| Third-party monitoring and risk management: literature review | Organizational design of risk management | Performance measurement in firms with decentralized risk management and risk-averse board |
| Review of monitoring literature with respect to the requirements for correct agency theoretical modelling of risk management | Impact of different organizational structures of risk management on firm's utility and risk and discussion of the optimal design | Disclosure of effects from incentivizing the risk managers with same contracts and performance measures as other types of managers |
| Published in Review of Economics | Accepted for publication in International Journal of Strategic Management | Published in European Journal of Management |

**Fig. 1 Objectives of the thesis.**

Thus, this thesis aims to address the problems of organization and incentivization of risk management by applying the agency theoretical models; Figure 1 summarizes its objectives and structure. The first study examines the extent to which the pre-existing monitoring literature allows insights and provides answers for risk management problems in firms, stating the existence of a literature gap. The second study implements the linear, exponential, normal (LEN) model of the agency theory to analyze how risk management should be optimally organized and which effects are observed in different organizational structures. The LEN model goes back to the seminal work of Spreman (1987) and, through its assumptions, allows a transition from the expected utilities of the actors to their certainty equivalents. As opposed to standard agency models, LEN models enable the computation of analyzable closed-form solutions. The third study expands the model to examine the problems arising from incentivizing RMs with the same PMs as other managers in firms. In this context, a simulation is proposed as an additional method to help analyze complex agency theoretical results. Hence, this thesis contributes to the agency theoretical literature by pointing toward risk management as a new research field and providing answers to certain questions within it.

## 1.2 Content

This work comprises three studies on risk management in firms. The first study summarizes the existing agency theoretical literature on monitoring by a third party, proposes the conditions under which the monitoring may be interpreted as risk management, and analyzes the literature with respect to these conditions (Chapter 2). The second study proposes two organizational structures of risk management—centralized and decentralized—and analyzes their effect on a firm's expected profit and risk. It also discloses the influence of managerial risk aversion on risk management (Chapter 3). The third and final study covers the impact on a firm's utility and the risk of incentivizing the RMs by the same contracts and PMs as other managers. It postulates and implements simulation as a research method complementary to formal analytical studies with complex results. It also regards the impact of the board's risk aversion on the analysis of risk management in firms (Chapter 4). Chapter 5 concludes.

*Study 1: Third-party monitoring and risk management: literature review (Chapter 2)*

To establish the extent of the literature gap, agency theoretical research on monitoring and supervision, understood as gaining better insight into the activities of the agents, is summarized, analyzed, and compared. Monitoring is closely related to the precision of the PMs, defined as the inverse of their variance. Thus, it can at times be seen as a variance-reducing activity. Accepting this as a starting point allows for a re-examination of the literature on monitoring concerning its applicability to risk management, that is, another variance-reducing activity of the firm.

The settings in the summarized articles are investigated with regard to three core aspects necessary to accurately model risk management in firms. First, the focus on the monitor as a risk- and effort-averse third party should guarantee accordance with the empirically observed practice of employing RMs as additional risk- and effort-averse managers in firms. Second, the demand for a connection between the PM used in managerial contracts and the firm's risk should reflect the fact that the monitor's activity must affect the firm's risk in some way to accept it as risk management. Finally, the risk aversion of the principal constitutes the original interest in organizing risk management, even though it is not indispensable, as the legal regulations can also induce it. The core result emerging from the analysis concerning these requirements is that hardly any literature exists on organization or incentivization of risk management in firms. However, two studies can be seen as approximating risk management: Meth (1996) and Dürr et al. (2020).

Meth (1996) is directly available for reinterpretation as risk management. The manager has two tasks, a mean-increasing and a variance-decreasing one, thus being simultaneously a BUM and an RM (or CEO and CRO). Underinvestment in one of these tasks is observed, immediately pointing out the potential inefficiencies from a delegation of other tasks beyond risk management to a manager. Meth (1996) also shows that managerial risk aversion influences the optimal incentive design: to induce more risk-taking in risk-averse managers, contracts based on stock options are important, whereas for risk-neutral managers, bonus plans with an upper bound are necessary to prompt them toward risk-managing activities.

In Dürr et al. (2020), the risk- and effort-averse monitoring managers may decrease the variance of the uncertain productivity of the team's joint output; the incentives to engage in this activity come from their contractual payment, contingent on the firm's outcome, understood as accounting income. The incentive contract aligns the risk of uncertain productivity with managerial compensation risk, and the manager's risk aversion prompts them to reduce this compensation risk. Furthermore, the principal is modeled as risk-averse. Even so, the risk of an accounting income is not quite the same as the risk of a whole firm, and managerial activity resembles market research rather than risk management. The lessons learned for risk management are restricted: an increase in the firm's risk leads to smaller teams in optimum if the manager is a project manager and RM simultaneously. Overall, risk management should be treated from the perspective of agency theory as a new area that is not sufficiently analyzed. This paves the path for the re-examination of many issues, as virtually none of the questions named in Chapter 1.1 has been sufficiently discussed in the context of risk management.

*Study 2: Organizational design of risk management (Chapter 3)*

Within institutional recommendations on risk management, two distinct designs emerge: risk management either through a board-level committee or by internal RMSs or CROs along the hierarchical tiers of the firm, employed in the individual business units (BUs). This study transforms these concepts into a model of centralized and decentralized risk management. In centralization, the RM is employed directly by the principal, whereas in decentralization, the contracting authority is delegated to a BUM, which in turn contracts with an RM. The analysis provides two insights for risk management: one regards managerial risk aversion as a factor influencing the incentives and results differently, depending on the organizational structure; the other concerns the optimal risk management structure.

Generally, an increase in RM's risk aversion leads to a decrease in incentives, in an effect typical of agency theory. However, it also directly prompts an RM to engage in more effort to decrease compensation risk. The overall effect depends on the organizational structure and cost of the risk-management effort. In centralization, the effects resulting from a change in RM's risk aversion balance each other perfectly so that RM's risk aversion remains irrelevant to the results. In decentralization, the RM is ready to provide more effort as risk aversion increases, only if the cost of risk-management effort is not too high. Moreover, an increase in BUM's risk aversion influences the effort of an RM as well, but indirectly through incentives: as the BUM's risk aversion increases, the party employing an RM (principal or BUM themselves) strengthens the incentives offered to the RM to offset this increase. Here, the effect in both structures follows the same pattern, with the party engaging the RM interested in incentivizing additional effort as the BUM's risk aversion increases, as long as the cost of this effort is not too high. From this perspective, managerial risk aversion emerges as being crucial for pre-existing organizational structures. The firms should take into consideration the possible cross-effects of risk aversion of some managers and the behavior of the others, especially RMs, while designing managerial incentives. Moreover, risk aversion should be accounted for in the recruitment processes in firms; similarly, testing for effort aversion may be of use. This is a distinct contribution to the second question from Chapter 1.1 on the individual characteristics relevant for incentivizing RMs.

If the organizational design of a firm can still be chosen or changed, the following must be accounted for: decentralization in all cases leads to higher firm's profit than centralization, but only to lower firm's risk than centralization if the cost of risk-management effort is high. For the high cost of risk-management effort, the principal in a centralized structure can afford neither the high productive incentives nor the necessary risk-management incentives. This is due to the marginal risk-management incentives necessary for one additional unit of productive incentives. These marginal incentives are lower in decentralization than in centralization, making risk management in decentralization less expensive from the perspective of the principal. Overall, as the risk-neutral principal is interested in optimizing profit, they will always opt for decentralization, the firm's risk disregarded. Nevertheless, the effect of organizational structure on a firm's risk should be considered.

Thus, as an answer to the first problem accounted for in Chapter 1.1, it can be mildly supported that the internal RMSs or CROs on the level of individual BUs are more profitable for the firm than relying exclusively on a board-level committee. The results are, of course, restricted because of the assumption of contractibility of a firm's outcome and the principal's risk neutrality. The regulations regarding the organization of risk management in firms often recommend the parallel use of centralized and decentralized structures, implying intuition toward joining the benefits of different risk management designs. Furthermore, the direct contractibility of a firm's outcome is assumed, which is a restrictive assumption, as the practice often uses PMs only to approximate it. The impact of contractual use of PMs other than a firm's outcome in the context of risk management remains an issue open to examination.

*Study 3: Performance measurement in firms with decentralized risk management and risk-averse board (Chapter 4)*

In the third and final study, the problem of incentivizing RMs in the absence of a contractible firm's outcome is analyzed. The model encompasses a board as a principal and a BUM with authority to contract with an RM within a decentralized structure; all parties are risk-averse. Managerial contracts are based on a PM correlated with a firm's outcome, and the risk-management effort decreases both the risk of a PM and that of the firm. Thus, we model monitoring with spillover in the form of risk management, guaranteed by the model design. As the results are highly complex, they are implemented in MS Excel's add-in Oracle Crystal Ball®. The relation of input and output is simulated in a multitude of trials, generating interpretable Spearman's rank correlation coefficients.

The results are relevant for future practice and research in three aspects. First, the risk aversion of the principal is crucial for modeling risk management in the absence of a contractible firm's outcome, establishing the board's motivation for risk management implementation. Risk neutrality of the principal severs all ties to risk management, transforming the model back to monitoring. Second, there are inefficiencies in basing contracts with different manager types on the same PMs. More precise PMs increase the firm's utility as they motivate additional productive effort. Meanwhile, less precise PMs elicit additional effort from RMs to decrease managerial compensation risk. Even though, in equilibrium, only the firm's utility is of relevance, and thus more precise PMs are preferred, this observation is still pertinent: it may be necessary to find unique contracting metrics for RMs, diverging from those applied to all other types of managers. Thus, the final question from Chapter 1.1 is addressed, even though no explicit recommendation on the design of performance measurement for RMs can be made. Third, this study presents a novel approach to the interpretation of highly complex analytical results. Simulation as a research method is already well known in agency theoretical research; nonetheless, the perception of these models as "black boxes" usually precludes wider acceptance. Through analytical computation of the model and use of simulation only to obtain the interpretable correlations between its inputs and outputs, some of this prejudice can be removed, leading to wider acceptance of the method itself and through its application to larger accessibility of complex and unapproachable models.

# 2 Third-party monitoring and risk management: literature review

*Marta Michaelis*

ABSTRACT

Although risk management is prevalent in organizations, agency theory studies on contractual relationships in firms fail to address it. Risk reduction is mostly discussed within the context of monitoring, understood as insight into the activities of subordinates. Hence, this literature review discusses 18 main analytical studies on monitoring, reviewing whether they can be reinterpreted as depicting risk management, thereby allowing for the transfer of gained insights. Accordingly, only Meth (1996) and Dürr et al. (2020) can be reinterpreted as such, bearing the following risk management implications: (1) risk management is vital for firms, as firm's risk affects employee incentive contracts, firm's utility, and optimal firm size; (2) risk attitudes of risk managers are crucial for designing incentive contracts, with incentives necessary for more (less) risk-averse agents to encourage risk-taking (risk reduction); and (3) risk management should be delegated as a task separate from other managerial activities. The other studies do not depict risk management. Therefore, many research subjects remain open for further examination, such as organizing risk management in hierarchies, delegating risk management as a task and incentivizing it when a firm's outcome is unavailable for contracting, and establishing the connection between the performance measures used in managerial contracts and the risk of a firm.

**Keywords:** risk management; monitoring; agency theory; literature review

**JEL Classifications:** D23, J33, M52

# 3 Organizational design of risk management

*Stefan Dierkes and Marta Michaelis*

ABSTRACT

Risk management is obligatory for listed firms in many countries; its implementation is the responsibility of the boards of firms. The risk management structures can comprise board-level committees, as well as internal risk management systems and/or Chief Risk Officers. Hence, an important characteristic of the organizational design of risk management is the degree of centralization, which affects the firm's profit and risk. Therefore, we distinguish between two extreme forms of risk management: centralized risk management with a risk manager at the board level and decentralized risk management with a risk manager at the business unit level. We analyze the effects of these organizational designs of risk management within the Linear Exponential Normal framework, with quality of risk management depending directly on the effort of the risk manager. In either setting, risk aversion positively affects the risk manager's incentives and efforts at a low risk-management effort cost. Regarding the expected profit of the firm, decentralization is always preferable to centralization. However, it only leads to lower risk for the firm if the risk-management effort cost is not too high. These results help assess alternative risk management designs, while explaining the empirically observed simultaneous use of different organizational structures for risk management.

**Keywords:** risk management; monitoring; delegation; organizational design

**JEL Classifications:** D23, J33, M52

## 3.1 Introduction

Most firms have complex organizational structures, including many hierarchical tiers with distinct delegation of tasks and contracting authority at each tier (Williamson 1975; Jensen and Meckling 1976). Managers must deal with multiple activities, including productive tasks, contracting, coordinating, supporting, and monitoring (Hofmann and Indjejikian 2018). Among managerial activities, risk management remains highly important, especially as risks are becoming increasingly multifaceted (Simkins and Ramirez 2008). A risk management system (RMS) is mandatory for firms listed on the stock exchange and further generally recommended for all small and medium-sized businesses as an element of corporate governance (OECD 2014). Finally, risk management has merit on its own, in the form of additional information and protection from loss (UNECE 2012). Managing risk in an integrated way leads to better decision-making, reduces risk, and in turn increases the firm's prosperity in terms of value or utility (Gordon et al. 2009; Hoyt and Liebenberg 2011). If understood as enterprise risk management (ERM), it is perceived by firms as a strategic resource (Karanja 2017). As far as risk managers (RMs) are concerned, they wield influence at the board level, helping with strategic decisions and facing complex, intertwined risks. Their roles have evolved from simply being experts in risk calculation into advisory functions, with diverse tasks focused on the fast-changing future (Arena et al. 2010). As their activities fundamentally contribute to the reduction of risk faced by the firm, they influence the decision framework of all employees.

The organizational literature delivers only ambiguous recommendations regarding the design of risk management, besides underlining its necessity for firms (Burnaby and Haas 2009; Fraser and Simkins 2016). Based on the legal requirements and recommendations for listed firms, risk management is typically the responsibility of the board, taking the form of board-level committees, and/or implementation of internal RMSs and/or Chief Risk Officers (CROs) (OECD 2014; Bennett 2017). Board-level committees correspond with employing an RM in a staff position, as an advisor to the board, that is at a higher hierarchical tier (Reavis 1969). We denote this organizational structure as the centralization of risk management. By contrast, internal RMSs or CROs are often engaged at single hierarchical tiers and in separate business units, which is tantamount to the decentralization of risk management (Arena et al. 2010; Schiller and Prpich 2014; Siegel 2018). Therefore, we can distinguish between the centralization and the decentralization of risk management as "pure" organizational structures of risk management. Until now, the effects of these pure organizational structures of risk management on the firm's expected profit and final risk have not been analyzed, even though the knowledge of these effects are essential for the organizational design of risk management in firms as a combination of these pure structures.

Thus, the organizational design of risk management, understood as incentivizing this task and delegating it within hierarchical tiers, constitutes the analytical scope of this paper. Our main contribution lies in the comparison between hierarchical structures of risk management in an agency model and the resulting recommendations for an optimal design. Furthermore, we analyze the core effects of delegating risk management to a risk- and effort-averse manager, her/his optimal incentives, the relevance of managerial risk aversion for the organizational choice of the firm, and the implications it may have for the design of an RMS, as well as for the recruitment process.

Generally, the decisions regarding managerial incentivization and compensation intertwine with those regarding the optimal hierarchical design. Insofar, the behavior of managers has to be considered in the process of analyzing the effects of organizational structures. One suitable theoretical foundation for analyzing such problems offers the agency theory, where managers are usually assumed as risk-averse as well as effort-averse (Holt and Laury 2002; Eckel and Grossman 2002, 2008; Dohmen et al. 2011; Charness et al. 2013). Research regarding risk reduction under this framework is usually restricted to decreasing the noisiness of performance measures (PMs) through a monitoring activity in situations where a firm's outcome is not available in contracts (e.g., Liang et al. 2008). This should lead to a more precise performance measurement and thus enhance the efforts of the agents. As a result, we regard risk management as a special case of monitoring. The core difference is that better insight into agents' efforts is not an aim in itself, but rather a spillover of activities focused on decreasing the firm's final risk. Therefore, the monitors should be compensated, at least partially, based on the firm's outcome, or the variances of the performance measure and the firm's outcome should be correlated. In these cases, decreasing noisiness through monitoring (e.g., Hofmann and Indjejikian 2018) simultaneously leads to a reduction in the firm's risk. Furthermore, shareholders may use the risk-management practices to monitor the activities of the business unit managers (BUMs), as shown in the recent survey-based paper of Sekerci and Pagach (2020). Overall, we can interpret all the effort put into monitoring as risk-management activities in which an agent is supposed to engage. Modeling risk management as a variance-reducing activity is in accordance with understanding risk as the effect of uncertainty on objectives and is in such form often found in empirical research on (enterprise) risk management (Prendergast

2002; Pagach and Warr 2010). Notably, Arena et al. note the perception of risks as “variances in financial results, embracing all events that might affect profit” in companies (Arena et al. 2010, p. 669).

The optimal organizational design under such a modeling framework has not been extensively discussed in the monitoring literature. One of the most prevalent areas of research is the (costly) control of the agent’s effort, which is enforced with a specific probability. It is usually modeled as a time-demanding but not an effort-demanding activity by the monitor (Calvo and Wellisz 1978; Qian 1994; Ziv 2000). Another area defines monitoring as the (costly) reporting of an additional signal, sometimes extended with truth-revealing mechanisms (Dye 1986; Baiman et al. 1987; Demski and Sappington 1989; Itoh 1993; Baldenius et al. 2002), which partially allows for the interpretation of monitoring as external auditing. In this literature stream, for an organization, the benefit of monitoring is gaining superior insight into the employees’ actions, not directly reducing the firm’s risk. In any case, the focus on risk-neutral and sometimes even effort-neutral monitors ignores problems such as incentivizing the manager and the interdependencies between incentives and the hierarchical organization of monitoring.

Some articles model risk- and effort-averse monitors, but focus on different problems, such as optimal team size (Liang et al. 2008; Dürr et al. 2020) or optimal task assignment (Schmid 2018). Closest to the thrust of our research paper are the articles of Friedman (2016) and Hofmann and Indjejikian (2018). Friedman discusses the influence of employing a Chief Financial Officer (CFO) responsible for the reporting system (which may be interpreted as risk management) on incentives and risk preferences. The analyzed structure resembles the centralization of risk management, with the risk manager (CFO) as a staff position. However, the CFO’s effort is observable by the CEO and influences her/his effort choice, which is not necessarily the case in reality. Hofmann and Indjejikian (2018) focus on delegating authority within a firm and on the different roles of BUMs as monitors, among others. The authors discuss the assignment of authority and optimal organizational structures, not in the context of the placement of the monitor within the structures, but rather with regard to the managerial span of control and PM characteristics. In this case, monitoring is not the only activity of the BUM. Above all, neither Friedman (2016) nor Hofmann and Indjejikian (2018) explicitly consider monitoring as risk management nor do they discuss its optimal organizational design.

Overall, the agency literature covers different structures of monitoring, partially corresponding to empirical observations on organization of risk management. In these cases, we could discuss a firm’s outcome as an available performance measure, thus linking the models to the idea of risk management. Nonetheless, monitoring still differs from risk management. Its focus lies in more precisely measuring performance and the effects of this increased precision, whereas the organizational design of risk management tries to define the optimal hierarchical structure. The ultimate goal of organization of risk management is optimally dealing with the overall risk faced by the firm. These issues have not been systematically and extensively examined in the literature to date.

Our model is placed within the LEN framework, with LEN denoting linear contracts, exponential utility functions, and normally distributed results (Spremann 1987; Holmström and Milgrom 1987, 1991). We assume that the board of directors represents the owners' interests perfectly and thus acts as the risk-neutral principal in this model. The board hires one agent, defined as a BUM, who has to engage in productive activity within a single business unit. Moreover, in accordance with the recommendations in the organizational literature, we further delegate risk-management activities to a lower-level agent, defined as the RM. We analyze two available structures: centralized risk management, carried out by an RM directly advisory to the board of directors, thus corresponding with the board-level committee, and decentralized risk management, in the form of an internal RMS, carried out by an RM employed by a BUM. Independent of the chosen structure, the effort of an RM directly corresponds with the board's opportunities to manage risk. Thus, more risk-management effort of the RM leads to lower final risk for the firm, measured by lower variance of the firm's outcome. With respect to the previous arguments, we choose a contractible firm's outcome as a performance measure and presuppose risk and effort aversion in the managers. We do not consider the issues of optimal team and firm size or multiple agents and activities, as only two agents—a BUM and an RM—are employed. As mentioned earlier, the reasons for firms to provide for risk management are complex. We assume a sufficiently large firm that needs to provide for risk management due to legal requirements, or due to comply-or-explain rules (OECD 2014). Thus, even though, intuitively, the board's risk aversion should prompt it to strive for risk reduction, we restrict our analysis to the aspects independent of the principal's attitude towards risk, assuming that the risk-neutral firm will provide for an RMS and is henceforth interested in organizing it to optimize firm's expected profit The advantage of this modeling is that we can analyze the effects of different organizational designs of risk management on the behavior of the managers and the risk independent of the possible risk aversion of the principal.[1]

[1] Lastly, as far as the modelling framework is concerned, accounting for a risk-averse principal does not change the general effects observed.

With this modeling framework, we obtained the following results. Generally, the risk aversion of the RM has a negative effect on her/his incentives, which is typically known as risk incentives tradeoff in the agency literature, abbreviated to the incentive effect hereafter. However, it also has a positive effect on the risk-management effort, denoted as risk aversion effect, as the RM has an inherent interest in diminishing her/his own risk.[2] Moreover, as the managerial incentives depend on one another, the increase in a BUM's risk aversion has a negative effect on the RM's incentives, denoted as the extended incentive effect. Nonetheless, a party contracting with an RM increases her/his incentives to counteract the increased BUM's risk aversion, constituting an extended risk aversion effect on the incentive level. The (extended) risk aversion effect prevails over the (extended) incentive effect when the cost of risk-management effort is sufficiently low, so that the risk-management effort increases with managerial risk aversion.

Regarding the profitability of the structures, the tradeoff between the BUM's and RM's incentives, denoted as productive and risk-management incentives, respectively, arises as a crucial factor. Centralization requires more marginal risk-management incentives for each additional unit of productive incentives, than decentralization. More risk management leads to a decrease in the firm's final risk and, consequently, in the managers' risk premiums, but it also compromises the available productive incentives. Decentralization, on the other hand, is characterized by additional risk-sharing possibility of the BUM and thus a BUM may in equilibrium offer lower risk-management incentives and still choose higher productive effort than the ones we observe in centralization. As long as the cost of the risk-management effort is not too high, the managerial incentives' tradeoff leads to a situation, in which – even though the productive incentives are low – they are accompanied by the higher risk-management incentives and effort and thus lower final firm risk in centralization than in decentralization. When these costs exceed the critical threshold, however, the productive incentives in centralization shrink so much against the productive incentives in decentralization that the risk-management incentives emerge lower than in decentralization as well, eventually leading to higher final risk for the firm. Overall, decentralization always emerges as more profitable than centralization thanks to the managerial incentives' tradeoff allowing for more productive incentives and higher expected profit. However, the higher expected profit for the firm is, under decentralization, counterbalanced by a higher final risk when the cost of the risk-management effort is low. Still, delegating contracting authority to the BUM and the RM's proximity to the

[2] Friedman (2016, p. 102) emphasises a similar motivational effect of risk aversion: "a more risk-averse CFO will work harder to improve the quality of the reporting system and thereby reduce the risk he is exposed to, all else equal."

risks she/he manages leads to better performance of the firm, overall, compared to employing an RM in a staff position. The beneficial managerial incentives' tradeoff leads to more effective risk management, even though this does not always translate to overall lower final risk for the firm. Overall, our findings on the effects of centralization and decentralization on risk and profit provide valuable insights for the organization of risk management.

The remainder of this paper is organized as follows. Chapter 3.2 describes two possible organizational structures in detail. The optimal results are derived and analyzed based on their core comparative statics. Moreover, risk aversion as a motivational factor is established. Chapter 3.3 compares core effects in both organizational structures and interprets the sources of their profitability. Chapter 3.4 concludes the paper, also identifying limitations and avenues for future research.

## 3.2 Model design and core effects

### 3.2.1 Model design and timing of events

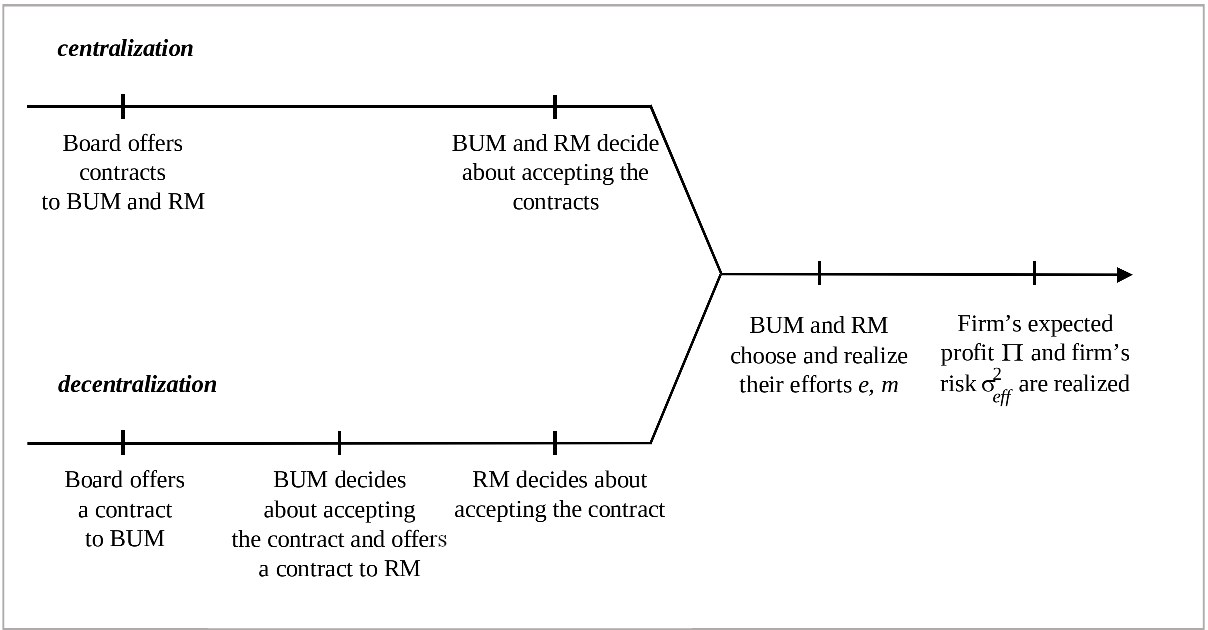


**Fig. 2 Timelines of the model under the different organizational structures.** Upper axis presents the initial steps of centralization: first, board offers contracts to BUM and RM, followed by managerial decisions on accepting the contracts. Lower axis presents the initial steps of decentralization: first, board offers a contract to BUM, followed by her/his decision about accepting the contract and offering a contract to RM, with RM's decision about accepting the contract as the final step. The timelines converge afterward, with managers choosing and realizing their efforts e and m, followed by realization of firm's expected profit Π and firm's final risk $\sigma^2_{eff}$.

We consider an organization with a risk-neutral board of directors and a productive BUM in a single-period setting. The board, representing the owner, delegates one task to the BUM, which influences the firm's outcome. Additionally, the board can implement one of two different risk-management organizational structures within the firm. First, it can organize a board-level committee by employing a risk manager as a staff position on the highest hierarchical tier of the organization, which we will refer to as centralization of risk management. In this case, the board has the authority to contract with the RM. Second, the board can delegate this authority to the BUM as the lower hierarchical tier, which reflects a decentralization of risk management in the form of internal RMSs or CROs in single BUs. The board is obliged to provide for an RMS and is thus interested in optimally organizing it with respect to the firm's expected profit. We summarize the timelines of our alternative designs in Figure 2.

Under centralization, the board hires an effort- and risk-averse BUM and RM, with constant absolute risk aversion $r_B$ and $r_R$, respectively.[3] The BUM provides unobservable productive effort $e \geq 0$ with marginal productivity $\alpha$, accompanied by private effort costs $0.5 \cdot e^2$. The firm's outcome is the outcome of the BUM:

$$\tilde{x} = \alpha \cdot e + \tilde{\varepsilon} \qquad (1)$$

with

$$\tilde{\varepsilon} \sim N\left(0, \frac{\sigma^2}{1+m}\right) \qquad (2)$$

as uncontrollable events. Within this term, the parameter $\sigma^2$ is the original risk of the firm that is to be managed. To this aim, the RM should engage in risk management with effort level $m \geq 0$ and private costs $k \cdot m$. Thus, the firm's final risk after risk-management, defined in (2) as the effective variance of the exogenous noise of the firm's outcome, is determined by RM's endogenous choice of $m$ in equilibrium.[4]

---

[3] The RM's risk aversion is an absolute necessity in our LEN framework, as the RM's incentives are based on the firm's outcome, but her/his efforts only contribute to a reduction in the firm's risk. Thus, a risk-neutral RM would not engage in any activity, regardless of her/his incentives. Under more general model, also a risk-neutral agent could be incentivized to provide a variance-reducing effort, i. e. through implementation of a non-monotone contract. The experimental results suggest that such contracts may be accepted by the agents and lead to optimal results (Brosig et al. 2010). Nonetheless, this contracting form is not typically found in the managerial contracts in practice; usually, output-based pay is used, as "in uncertain environments, there are no other good measures by which to align incentives" (Prendergast 2002, p. 1073). Moreover, managerial research widely accepts the assumption of linear contracts, even though it systematically excludes some optimal, non-linear contracts, due to the benefits of the results' tractability within the LEN modelling framework. Thus, we choose to model the contract offered to an RM as linear as well, in accordance with the contracting practice in the real world and modelling practices in managerial research.

[4] Managers are identical in all respects, including the potential cost of risk-management effort, with the only difference between them being the grade of their risk aversion. The cost functions are inherent to the activities, not to the managers, with the convex function for cost of productive effort and linear function for cost of risk-

The managers are compensated based on the performance measure *x*, equal to the firm's outcome, under the following contracts, which are linear in all available outcomes:

$$v_B\left(\tilde{x}\right) = a_B \cdot \tilde{x} + b_B \tag{3}$$

for BUM and

$$v_R\left(\tilde{x}\right) = a_R \cdot \tilde{x} + b_R \tag{4}$$

for RM. The parameter *b* represents base salary of the managerial compensation, whereas the parameter *a* indicates the incentive rates for the firm's outcome. Thus, the risk-management effort simultaneously decreases the risk faced by the firm and the uncertainty of managers' compensation. Furthermore, the efforts are not directly observable or verifiable; we exclude the possibility of side contracting between the managers and normalize all managers' outside options to zero. We summarize our key notation in Table 1.

| | |
|---|---|
| | **variables** |
| $a$ | incentive rate |
| $b$ | base salary |
| $CE$ | certainty equivalent |
| $e$ | effort of the BUM |
| $k$ | risk-management effort cost |
| $m$ | effort of the RM |
| $r$ | coefficient of absolute risk aversion |
| $s$ | managerial incentives' tradeoff |
| $v$ | managerial contract |
| $x$ | firm's outcome |
| $\alpha$ | marginal productivity of the BUM's effort |
| $\varepsilon$ | error term denoting uncontrollable event |
| $\Delta$ | differences |
| $\Pi$ | firm's expected profit |
| $\sigma^2$ | firm's risk before risk management |
| $\omega$ | auxiliary variable for parameter bounds |
| | **sub-/ superscripts** |
| $c$ | sub-/ and superscript denoting centralization |
| $d$ | sub-/ and superscript denoting decentralization |
| $B, R$ | subscript denoting BUM/RM |
| $eff$ | subscript denoting firm's final risk (effective variance) |
| * | in optimum |

**Tab. 1 Summary of key notations.**

Both managers strive to maximize their utilities, which under the given assumptions is the same as maximizing their certainty equivalents, respectively characterized by

$$CE_B^c = E\left[v_B\left(\tilde{x}\right)\right] - \frac{1}{2}\cdot\left(e^c\right)^2 - \frac{1}{2}\cdot r_B \cdot Var\left[v_B\left(\tilde{x}\right)\right] \tag{5}$$

management effort chosen for tractability. Moreover, linear function corresponds with the personal benefit of an RM from the risk-management effort, which is increasing and concave in *m* (see Liang et al. 2008, p. 797).

and

$$CE_R^c = E\left[v_R\left(\tilde{x}\right)\right] - k \cdot m^c - r_R \cdot Var\left[v_R\left(\tilde{x}\right)\right] \ . \tag{6}$$

The board determines the optimal compensation contracts in a way that maximizes the firm's expected profit, subject to the BUM's and RM's participation and incentive constraints. We summarize it in the following optimization problem for the board:[5]

$$\begin{aligned} &\max_{a_B^c, a_R^c} \quad \Pi^c = E\left[\tilde{x} - v_B\left(\tilde{x}\right) - v_R\left(\tilde{x}\right)\right] \\ &s.t. \quad \left(PC_B\right): CE_B^c\left(e^{c,*}\right) \geq 0, \qquad \left(PC_R\right): CE_R^c\left(m^{c,*}\right) \geq 0, \\ &\qquad \left(IC_B\right): e^c \in \arg\max_{e^{c,*} \in E}\left\{CE_B^c\left(e^{c,*}\right)\right\}, \quad \left(IC_R\right): m^c \in \arg\max_{m^{c,*} \in M}\left\{CE_R^c\left(m^{c,*}\right)\right\}. \end{aligned} \tag{7}$$

Due to the participation constraints, the managers accept contracts rather than refuse them. From the incentive constraints, we derive optimal efforts $e^{c,*}$ and $m^{c,*}$, given contracts $v_B$ and $v_R$. Within this model, we obtain the results in Lemma 1 in a straightforward way:[6]

**Lemma 1** When the risk-management activity is delegated to the RM within centralization, then the BUM's productive effort is defined as

$$e^c = \alpha \cdot \left(1 - \frac{2 \cdot \sqrt{r_B \cdot k \cdot \sigma^2}}{\alpha^2}\right) , \tag{8}$$

with her/his incentive contract

$$a_B^c = 1 - \frac{2 \cdot \sqrt{r_B \cdot k \cdot \sigma^2}}{\alpha^2} \ . \tag{9}$$

The RM's effort is defined as

$$m^c = \left(\frac{1}{2} - \frac{\sqrt{r_B \cdot k \cdot \sigma^2}}{\alpha^2}\right) \cdot \sqrt{\frac{r_B \cdot \sigma^2}{k}} - 1 \ , \tag{10}$$

with her/his incentive contract

$$a_R^c = \frac{1}{2} \cdot \sqrt{\frac{r_B}{r_R}} \cdot a_B^c = \frac{1}{2} \cdot \sqrt{\frac{r_B}{r_R}} \cdot \left(1 - \frac{2 \cdot \sqrt{r_B \cdot k \cdot \sigma^2}}{\alpha^2}\right) \ . \tag{11}$$

---

5 In all organizational structures, we observe the trivial first-best result $e^{FB} = \alpha,\ a^{FB} = 0,\ a_R^{FB} = 0,\ m^{FB} = 0$ as the board may specify the observable first-best effort and risk management does not add any benefit to the solution. Therefore, we only discuss the second-best results.

6 The solution is given for a certain, sufficiently low cost of risk-management effort. When the cost of risk-management effort was too high, the efforts in equilibrium would be negative, thus no contracting would occur. We provide the derivation of Lemma 1 in the Appendix A1 and present the relevant bounds in the Appendix A2.

Finally, the firm's final risk after risk-management is

$$\sigma^2_{eff,c} = \left( \frac{1}{2} \cdot \sqrt{\frac{r_B}{k \cdot \sigma^2}} - \frac{r_B}{\alpha^2} \right)^{-1}, \tag{12}$$

with the firm's expected profit defined as

$$\Pi^c = \frac{1}{2} \cdot \alpha^2 \cdot \left( a_B^c \right)^2 + k = \frac{1}{2} \cdot \alpha^2 \cdot \left( 1 - \frac{2 \cdot \sqrt{r_B \cdot k \cdot \sigma^2}}{\alpha^2} \right)^2 + k. \tag{13}$$

Under decentralization, the board of the firm hires an effort- and risk-averse BUM. Additionally, it requires the BUM to hire an effort- and risk-averse RM, who should engage in risk management.[7] The rest of the framework is identical to that of centralization.

The BUM must weigh the profits from lower effective variance, lower risk premium, and her/his own higher incentives against the costs of incentivizing the RM. The BUM determines the optimal compensation contract for the RM, as well as her/his own productive effort, so that her/his certainty equivalent is maximized, subject to the RM's participation and incentive constraints, which we derive from the RM's certainty equivalent in (6). We denote the optimization problem of the BUM as follows:

$$\begin{aligned} \max_{e^d, a_R^d} \quad & CE_B^d = E\left[ v_B(\tilde{x}) - v_R(\tilde{x}) \right] - \frac{1}{2} \cdot \left( e^d \right)^2 - \frac{1}{2} \cdot r_B \cdot Var\left[ v_B(\tilde{x}) - v_R(\tilde{x}) \right] \\ s.t. \quad & \left( PC_R \right) : CE_R^d \left( m^{d,*} \right) \geq 0 \\ & \left( IC_R \right) : m^d \in \arg\max_{m^{d,*} \in M} \left\{ CE_R^d \left( m^{d,*} \right) \right\}. \end{aligned} \tag{14}$$

The board determines the optimal compensation contracts for the BUM in a way that maximizes the firm's expected profit, subject to the BUM's participation and incentive constraints. We summarize this in the following optimization problem for the board:

$$\begin{aligned} \max_{a_B^d} \quad & \Pi^d = E\left[ \tilde{x} - v_B(\tilde{x}) \right] \\ s.t. \quad & \left( PC_B \right) : CE_B^d \left( e^{d,*} \right) \geq 0 \\ & \left( IC_B \right) : e^d \in \arg\max_{e^{d,*} \in E} \left\{ CE_B^d \left( e^{d,*} \right) \right\}. \end{aligned} \tag{15}$$

Within this model, we obtain the following results through backward induction:[8]

---

7 According to Hofmann and Indjejikian (2018), contracting with subordinates is one of the managerial activities. Similar with their modelling framework, the BUM determines and pays the wages of the RM from the compensation pool provided by the board.

8 Similar to centralization, the solution is given for a certain, sufficiently low cost of risk-management effort, with derivation provided in Appendix A5 and relevant bounds presented in the Appendix A6.

**Lemma 2** When the risk-management activity is delegated to the RM under decentralization, the BUM's productive effort is defined as

$$e^d = \alpha \cdot \left(1 - \left(\sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1\right) \cdot \frac{r_B}{\alpha^2} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}}\right), \tag{16}$$

with her/his incentive contract

$$a_B^d = 1 - \left(\sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1\right) \cdot \frac{r_B}{\alpha^2} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \ . \tag{17}$$

The RM's effort is defined as

$$m^d = \left(1 - \left(\sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1\right) \cdot \frac{r_B}{\alpha^2} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}}\right) \cdot \sqrt{\frac{r_B \cdot \sigma^2 \cdot r_R}{(r_B + 4 \cdot r_R) \cdot k}} - 1, \tag{18}$$

with her/his incentive contract

$$a_R^d = a_B^d \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} = \left(1 - \left(\sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1\right) \cdot \frac{r_B}{\alpha^2} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}}\right) \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} \ . \tag{19}$$

Finally, the firm's final risk after risk management is

$$\sigma^2_{eff,d} = \left(\sqrt{\frac{r_B \cdot r_R}{k \cdot (r_B + 4 \cdot r_R) \cdot \sigma^2}} - \left(1 - \sqrt{\frac{r_B}{(r_B + 4 \cdot r_R)}}\right) \cdot \frac{r_B}{\alpha^2}\right)^{-1}, \tag{20}$$

with the firm's expected profit defined as

$$\Pi^d = \frac{1}{2} \cdot \alpha^2 \cdot \left(a_B^d\right)^2 + k = \frac{1}{2} \cdot \alpha^2 \cdot \left(1 - \left(\sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1\right) \cdot \frac{r_B}{\alpha^2} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}}\right)^2 + k \ . \tag{21}$$

### 3.2.2 Influence of risk aversion on managerial incentives and effort

To understand the relevance of managerial risk aversion for the firm's expected profit and final risk, as well as the source of the profitability of one structure over the other, we need to discuss certain observable effects.[9] First, an increase in risk aversion has a straightforward negative effect on managerial incentives and effort, which we call incentive effect hereafter. This effect is identical to the risk incentives tradeoff generally observed in agency models. However, our incentive effect does not transition completely to the risk-management effort, as the increase in

[9] The derivation of the effects is provided in the Appendix A3 for centralization and Appendix A7 for decentralization. Discussion is further based on the analysis of comparative statics from Table 9 and Appendix A4 for centralization, as well as Table 10 and Appendix A8 for decentralization.

RM's risk aversion intrinsically motivates a risk-averse RM to exert additional effort. We call this the risk aversion effect. Thus, the risk-management effort may increase as the RM's risk aversion increases, but only as long as her/his cost of effort is sufficiently low, as in these cases, the risk aversion effect outweighs the incentive effect.[10] Risk aversion is then an additional motivational factor for the RM, as noted by Friedman (2016). For the BUM, we find no risk aversion effect, as it is found in the agency literature.

Furthermore, from (11) and (19), we can distinguish that managerial incentives depend on one another. We interpret and summarize this interdependence in the following definition:

**Definition** One additional unit of BUM's incentives, denoted as productive incentives, must be accompanied by additional marginal RM's incentives, denoted as risk-management incentives, with the precise extent being determined by the managerial incentives' tradeoff of

$$s^c = \frac{\partial a_R^c}{\partial a_B^c} = \sqrt{\frac{r_B}{4 \cdot r_R}} \tag{22}$$

in centralization and by the managerial incentives' tradeoff of

$$s^d = \frac{\partial a_R^d}{\partial a_B^d} = \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} \tag{23}$$

in decentralization.

The interdependence of incentives leads to cross-effects between the risk aversion of one manager and the incentives of the other. Thus, when the risk aversion of the BUM increases, we observe an extended BUM-related incentive effect, weakening the possible risk-management incentives. We further find an extended BUM-related risk aversion effect. The difference between the extended and the original risk aversion effect is that the extended one is induced at the incentive level. What drives the RM to exert more effort is not her/his risk aversion, but rather the endeavors of a third party, contracting with the RM, to partially counteract the effects of an increase in the BUM's risk aversion. Stronger incentives should lead to higher risk-management effort, lowering the firm's risk and thus moderating the

[10] Please see the appendices for the precise definitions of the "low" and "high" cost of the risk-management effort for all structures. The range of the cost of risk-management effort, for which the risk management intensifies with increasing risk or risk aversion, is especially wide for high productivity of effort, low managerial risk aversion, and low original risk for the firm. In these cases, RM's sensibility for an increase in these parameters is higher and she/he is readier to intensify risk management, thus the cost at which it is still profitable is also higher.

negative effect of an increase in the BUM's risk aversion. As in the previous case, the extended, BUM-related risk aversion effect outweighs the extended BUM-related incentive effect only for a sufficiently low cost of risk-management effort.[11]

As far as the influence of other input parameters is concerned, it is vastly similar in both organizational structures. Increase in cost of risk-management effort has uniform negative influence on the results, reducing optimal incentives, effort and the firm's expected profit, while increasing the firm's final risk. The opposite is the case, if the productivity of the BUM's effort increases. As far as the initial risk that is to be managed is concerned, its increase always reduces the incentives, thus diminishing the optimal effort and the firm's expected profit. The influence on the risk-management effort, however, is more sophisticated. Even though an increase in the original variance diminishes the incentives for the RM, the risk-management effort increases, as long as its cost is not too high, due to risk aversion effect prevailing over the incentive effect.

## 3.3 Comparison and defining optimal organizational structure

### 3.3.1 Influence of incentive and risk aversion effects on firm's expected profit and risk

In this section, we analyze and discuss the (extended) risk aversion and incentive effects for both structures in order to emphasize their influence on the firm's expected profit and final risk. We provide examples and figures, which shed further light on the concept of "low" and "high" risk-management effort costs.

For the RM's risk aversion, we derive:

$$\frac{\partial m}{\partial r_R} = \underbrace{\frac{\partial a_R}{\partial r_R} \cdot \sqrt{\frac{\sigma^2 \cdot r_R}{k}}}_{\substack{<0 \\ \text{incentive effect}}} + \underbrace{\frac{a_R}{2} \cdot \sqrt{\frac{\sigma^2}{k \cdot r_R}}}_{\substack{>0 \\ \text{risk aversion effect}}} \begin{cases} = 0 & \text{in centralization} \\ \geq 0 & \text{for low k in decentralization} \\ < 0 & \text{for high k in decentralization.} \end{cases} \quad (24)$$

In centralization, we can directly observe that the incentive and risk aversion effects balance each other perfectly. The intrinsic motivation increases only to the extent that the loss in the incentives, motivated by an increase in risk aversion, is covered. In decentralization, for a low cost of risk-management effort, we distinguish an increase in this effort as the risk aversion effect prevails over the incentive effect. For a high cost of risk-management effort, the opposite is the case. Nonetheless, in decentralization, an increase in the RM's risk aversion has an overall

[11] We find extended RM-related incentive and risk aversion effects as well. However, the incentive effect in this case always prevails over the risk aversion effect. Therefore, in contrast to the BUM-related effects, there is no surprising positive influence observable, and thus no additional analysis is necessary.

negative effect on the results as the RM's risk premium increases. Even if the RM's effort has a low cost, the indirect effect of an increase in this effort does not outweigh the direct effect of the higher risk aversion coefficient, although it decreases the firm's final risk and thus the effective variance of the managerial performance measure. A higher risk premium for the RM harms the productive incentives that may be offered to the BUM. Thus, the productive incentives, effort, and the firm's expected profit decrease with the RM's risk aversion, even when the firm's final risk decreases as well for a low cost of risk-management effort. In comparison, centralization protects the results from fluctuation in the RM's risk aversion.

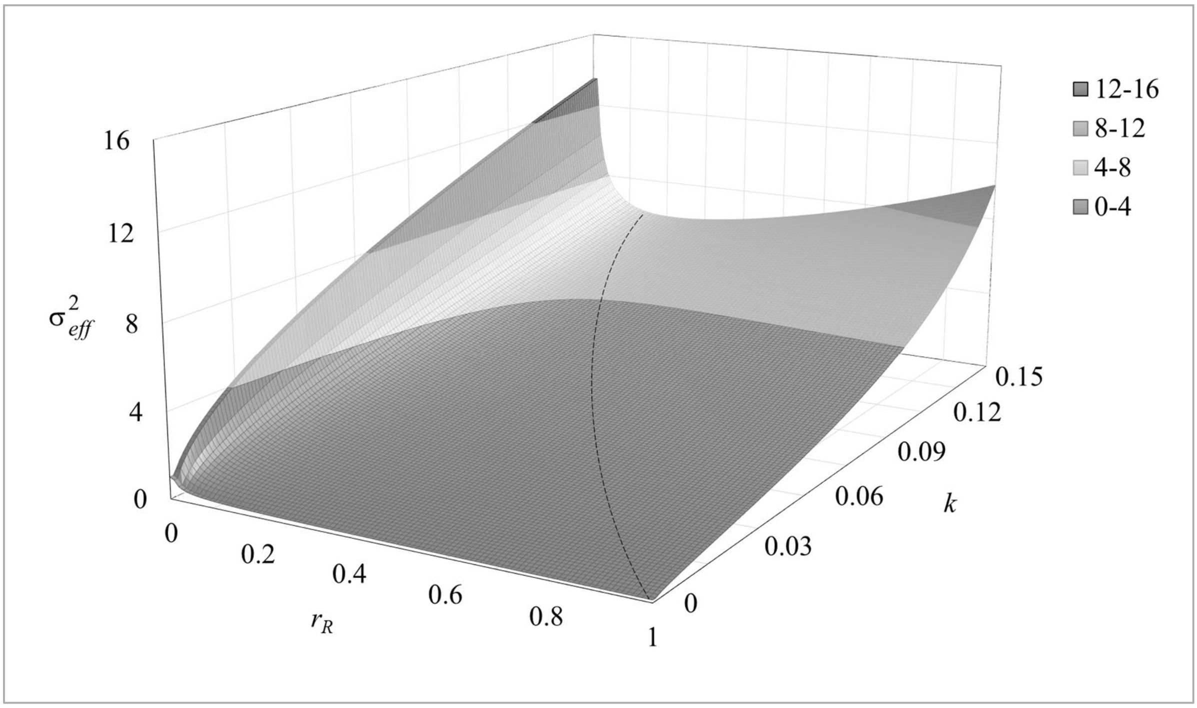


**Fig. 3** **Risk aversion effect under decentralization** with $\sigma^2 = 2$, $\alpha = 0.8$ and $r_B = 0.4$. The graph shows how the firm's final risk $\sigma^2_{eff}$, changes, when RM's risk aversion $r_R$ and her/his effort cost k change. It is plain to see, that increase in k leads to higher final risk for the firm, as the RM's effort decreases. Generally, the increase in RM's risk aversion influences her/his incentives and thus effort negatively (incentive effect), but simultaneously strengthens her/his inner motivation to exert additional effort (risk aversion effect). For low k, the risk aversion effect prevails over incentive effect and RM exerts additional effort in spite of reduced incentives, reducing also the firm's final risk. For high k, the opposite is true. The threshold between low and high risk-management effort cost depends on the other input parameters in the model and is characterized with the dotted line on the graph. The effect is present only in decentralization, whereas in centralization no effect on RM's risk aversion on the firm's final risk is found.

We reflect the relevance of the risk aversion effect for the firm's final risk and the interdependence of risk aversion and the cost of risk-management effort in the example presented in Figure 3. For the calculation, we assume the initial variance to be $\sigma^2 = 2$, the productivity of productive effort $\alpha = 0.8$, and the risk aversion of the BUM $r_B = 0.4$. For a given level of RM's risk aversion, we find that the firm's final risk is lowest when the cost of risk-management effort is at its lowest and that it increases with this cost. An increase in risk aversion enhances the inner motivation and it prevails over the diminished incentives, as long as the cost of risk-management effort is not too high. This is visible in the firm's high final risk for low risk aversion and its sharp decrease as risk aversion increases. The dotted line presents the threshold for the cost of effort for each given grade of risk aversion, from which the incentive effect prevails over the risk aversion effect. When the threshold for the cost of risk-management effort is crossed, the incentive effect starts to prevail over the risk aversion effect. Inner motivation, albeit present, is not strong enough to counteract the negative effect that risk aversion has on the incentives, leading to a decrease in the risk-management effort. Thus, from this threshold on, the firm's risk begins to increase again. Overall, especially for a low cost of risk-management effort, the beneficial effects of the increase in RM's risk aversion for the firm's final risk are straightforward.[12]

For the BUM's risk aversion, we derive the extended incentive and extended risk aversion effects:

$$\frac{\partial m^c}{\partial r_B} = \left( \underbrace{\frac{\partial a_B^c}{\partial r_B} \cdot \frac{1}{2} \cdot \sqrt{\frac{r_B}{r_R}}}_{\substack{<0 \\ \text{extended incentive effect}}} + \underbrace{\frac{a_B^c}{4 \cdot \sqrt{r_R \cdot r_B}}}_{\substack{>0 \\ \text{extended risk aversion effect}}} \right) \cdot \sqrt{\frac{\sigma^2 \cdot r_R}{k}} \quad \begin{cases} \geq 0 \text{ for low k} \\ < 0 \text{ for high k} \end{cases} \tag{25}$$

$$\frac{\partial m^d}{\partial r_B} = \left( \underbrace{\frac{\partial a_B^d}{\partial r_B} \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}}}_{\substack{<0 \\ \text{extended incentive effect}}} + \underbrace{a_B^d \cdot \frac{2 \cdot r_R}{\sqrt{r_B \cdot \left(r_B + 4 \cdot r_R\right)^3}}}_{\substack{>0 \\ \text{extended risk aversion effect}}} \right) \cdot \sqrt{\frac{\sigma^2 \cdot r_R}{k}} \quad \begin{cases} \geq 0 \text{ for low k} \\ < 0 \text{ for high k.} \end{cases} \tag{26}$$

In both structures, with an increase in the BUM's risk aversion, the party contracting with an RM wishes to incentivize more risk management. Risk-management activities lead to lower final risk for the firm, as long as the cost of risk-management effort is sufficiently low. Nonetheless, as above, the direct influence of increased BUM's risk aversion outweighs the lower effective variance, leading to higher BUM's risk premium, thus negatively influencing productive incentives, effort, and the firm's expected profit.

[12] The figures do not depict the entire range of the permissible cost of risk-management effort. As this cost increases, the results are only defined for the lower risk aversion coefficients. Including this range would not help interpretation of the figures and could hinder their readability.

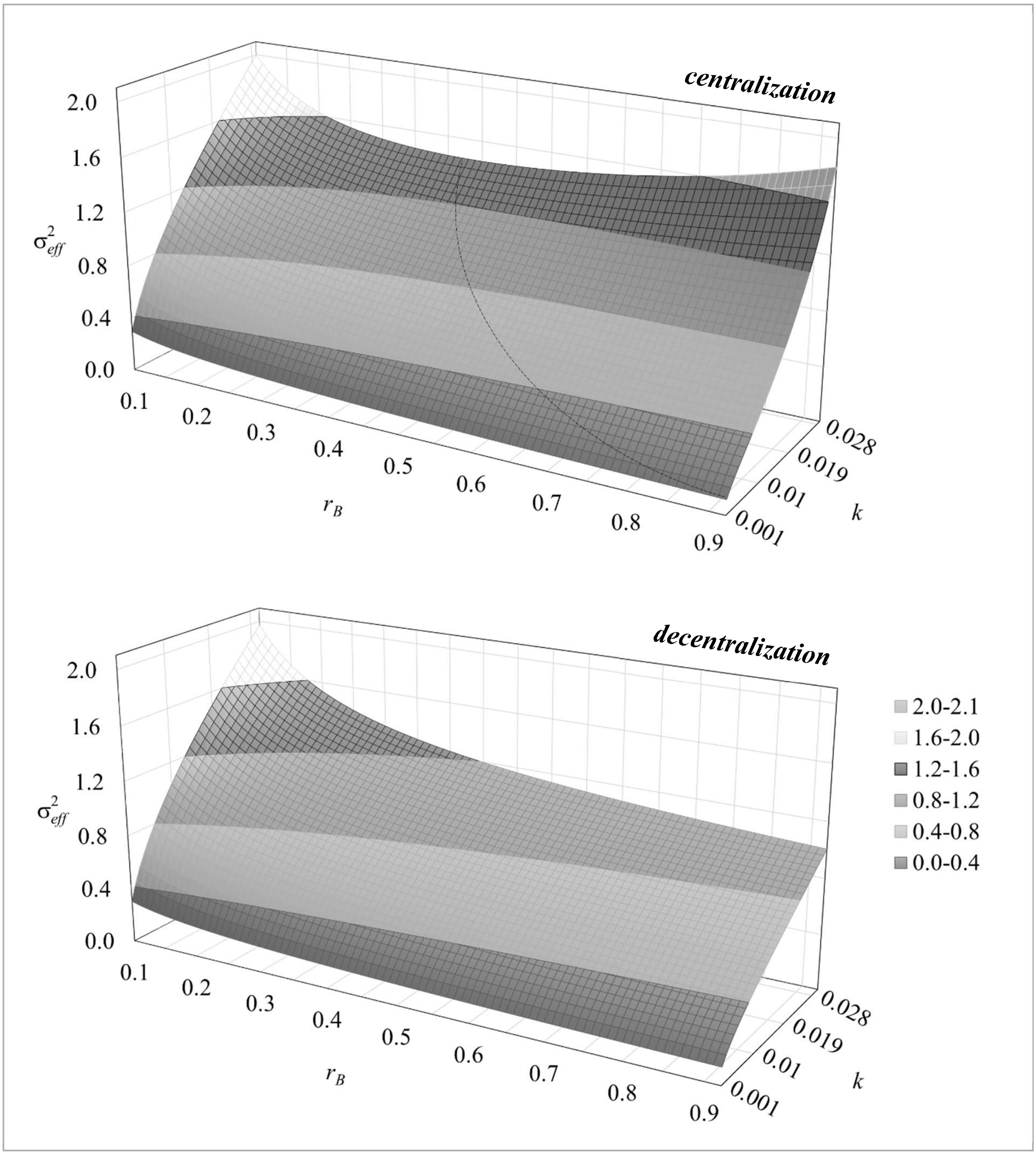


**Fig. 4** **Extended BUM-related risk aversion effect under centralization and decentralization** with $\sigma^2 = 2$, $\alpha = 0.8$ and $r_R = 0.4$. The graphs show how the firm's final risk $\sigma^2_{eff}$, changes, when BUM's risk aversion $r_B$ and RM's effort cost k change, with upper (lower) graph depicting centralization (decentralization). It is plain to see, that increase in k leads to higher final risk for the firm, as the RM's effort decreases. Generally, the increase in BUM's risk aversion influences her/his incentives and thus, in turn, RM's incentives and effort negatively (extended BUM-related incentive effect), but simultaneously motivates the party providing the risk-management incentives (the board in centralization, the BUM in decentralization) to counteract this effect by strengthening RM's incentives to motivate an additional risk-management effort (extended BUM-related risk aversion effect). In centralization, for low k, the extended risk aversion effect prevails over the extended incentive effect and RM's incentives increase, leading to an additional effort, thus reducing the final risk for the firm. For high k, the opposite is true. The threshold between low and high risk-management effort cost depends on the other input parameters in the model and is characterized with the dotted line on the graph. In decentralization, the same could be observed first for higher risk-management effort cost, which are not depicted in order to retain comparability between both graphs.

We depict the extended risk aversion effect in the example presented in Figure 4. For the calculation, we assume initial variance to be $\sigma^2 = 2$, productivity of productive effort $\alpha = 0.8$, and risk aversion of the RM $r_R = 0.4$. In both graphs, very low risk aversion does not induce much risk-management effort, and the firm's final risk increases as the cost of the risk-management effort rises. A board, employing a BUM who is not very risk-averse is not interested in inducing higher risk-management effort, even at a low risk-management effort cost, because risk premiums are low either way. However, it incentivizes it more, as soon as the BUM's risk aversion increases, which is visible in the sharp decrease in the firm's final risk for lower grades of risk aversion in both graphs. In the first graph, under centralization, the dotted line marks the threshold from which the extended incentive effect prevails over the extended risk aversion effect and the board cannot afford stronger risk-management incentives. We do not observe this in the second graph, under decentralization; after an increase in the BUM's risk aversion, if the BUM finds the cost of risk-management effort is still low enough to employ an RM profitably, this increase in risk aversion will lead to an overall lower final risk for the firm.

### 3.3.2 Comparison of firm's expected profit and risk

In this section, we compare the organizational structures of risk management and identify the optimal one with respect to the firm's expected profit. Overall, the cost of risk-management effort is crucial for the comparison between the structures with respect to the firm's final risk, whereas with respect to the firm's expected profit we are able to identify the optimal structure unambiguously. Under both structures, the overall effect of the increase in risk aversion on productive incentives, productive effort, and the firm's expected profit remains negative. This negative influence is, however, less severe for a low cost of risk-management effort, when the increase in risk premiums is partially counteracted by lowered effective variance due to the (extended) risk aversion effect.

Generally, the reservation utility, covering the effort costs and risk premiums, must be granted to the managers in all cases. When the RM is employed by the BUM, her/his reservation utility is transferred through the BUM's reservation utility to the board. Therefore, in effect, the board must in all cases directly or indirectly cover both reservation utilities. Nonetheless, the composition of the costs within the firm's expected profit differs between the structures. In particular, the necessary managerial incentives' tradeoff harms the incentives that could be offered to the BUM, with the extent of this harm determined by the chosen structure. On the one hand, stronger productive incentives induce stronger risk-management incentives and effort, diminishing the managerial compensation risk, which in return further enhances the incentives. On the other hand, providing risk-management incentives necessarily results in shrinking the means from which the productive incentives are offered. Overall, lower marginal risk-management incentives are required in decentralization than in centralization, as seen in Proposition 1. The proof is straightforward and follows directly from the previous Definition.

**Proposition 1** For each additional unit of productive incentives, more marginal risk-management incentives are required in centralization than in decentralization: $s^c > s^d$.

Diverging managerial incentives' tradeoff results from the possibility of BUM in decentralization to directly influence the risk she/he faces. From Equation (14) it is clear, that the compensation risk of the RM diminishes the risk of the BUM, indicating that she/he may transfer the risk to the lower hierarchical tier. In centralization, this option for additional risk-sharing is missing and the BUM cannot directly influence the risk-management incentives.

Furthermore, as seen in (24), a firm with centralized risk management is secured from fluctuation in RM's risk aversion, as changes within it only influence the risk-management incentives and are extinguished within the risk-management effort. Due to the unavailability of additional risk-sharing, overall stronger incentives are generally required, inducing more risk management and lower risk for the firm than in decentralization. On the other hand, in decentralization, when the cost of risk-management is low, the intrinsic motivation of the RM combined with availability of additional risk-sharing on the part of the BUM, lead to weaker risk-management incentives necessary in equilibrium. As the cost of risk-management effort increases, the productive incentives and effort decrease in both structures, and decentralization loses the positive influence of the risk aversion effect outweighing the incentive effect. Considering the requirement of more risk management, however, productive incentives suffer more in centralization; thus, even within the required managerial incentives' tradeoff, the risk-management incentives become weaker compared to that in decentralization. Overall, for a low cost of risk-management effort, centralization leads to lower firm's final risk than decentralization, as defined in Proposition 2.[13]

[13] We provide proof of Proposition 2 in Appendix A9.

**Proposition 2** When the risk-management activity is delegated to the RM within centralization, then the RM provides more risk-management effort, leading to a lower final risk for the firm than when the risk-management activity is delegated to the RM within decentralization, as long as the cost of the risk-management effort is sufficiently low.[14] Specifically, $a_R^c \geq a_R^d$, $m^c \geq m^d$ and $\sigma^2_{eff,c} \leq \sigma^2_{eff,d}$ for all $k$'s, so that

$$\sqrt{k} \leq \left( \frac{\sqrt{r_B + 4 \cdot r_R}}{2} - \sqrt{r_R} \right) \cdot \sqrt{\frac{1}{\sigma^2} \cdot \frac{\alpha^2}{r_B}}. \tag{27}$$

As seen in Proposition 1, managerial incentives' tradeoff allows for stronger productive incentives in decentralization, so that this structure is more profitable than centralization in terms of the firm's expected profit, as seen in Proposition 3:[15]

**Proposition 3** When the risk-management activity is delegated to the RM within decentralization, then the BUM provides more productive effort, leading to higher expected profit for the firm than when the risk-management activity is delegated to the RM within centralization.

Thus, overall, in order to cover the stronger risk-management incentives required, the productive incentives shrink, lowering the firm's expected profit in centralization. Moreover, for a high cost of risk-management effort, all incentives eventually become higher in decentralization compared to centralization, leading to not only higher expected profit but also lower final risk for the firm in this structure. The main disadvantage of centralization is the inability of the board to provide stronger incentives due to the tradeoff between both types of incentives in the absence of additional risk-sharing possibilities on the side of the BUM. The proximity of the RM to the risks she/he manages, as in decentralization, as well as the additional possibility of a risk transfer between the managers, lead to overall better performance by the firm in decentralization, even though the firm's overall final risk is not always lower.[16] This

[14] Comparison is only possible, when the cost of risk-management effort is below bounds set in both structures. Only then, both structures are theoretically available and the board may choose at all. Further, as the bounds depend on the input parameters, two cases are possible, with details shown in the Appendix A9. When the bound of the Proposition 2 is smaller than bounds required in both available structures, then we observe the result as defined in the Proposition 2. In all other cases, with both structures theoretically available, the RM always provides more risk-management effort, leading to a lower final risk for the firm in centralization than in decentralization.

[15] We provide proof of Proposition 3 in Appendix A10.

[16] As mentioned previously, a comparison is only possible, when both structures are available. This is the case, when the cost of risk-management effort is sufficiently low, specifically below the bounds determined by the requirement of non-negative efforts in each structure. Should decentralization require the cost of risk-management effort below the one required by centralization, it can occur, that the characteristics of the agents

provides us with an intuition as to why the combination of both organizational structures is usually found in legal recommendations, with board-level committees used simultaneously with internal RMSs and CROs in single BUs.

The cost of risk-management effort and the risk aversion of managers drive the profitability of organizational structures. These findings could be reflected in the firms' recruitment processes. There is a vast literature on firm-manager matching (Rosen 1982; Terviö 2008), which recognizes the role of risk aversion in this process (Bernard et al. 2016; Hoitash et al. 2016). Procedures to test for effort aversion, similar to the diverse experimentally and empirically proven methods to test for risk aversion (Eckel and Grossmann 2002, 2008; Dohmen et al. 2011; Charness et al. 2013; Wang 2015; Bodnar et al. 2019), can be developed (Comerford and Ubel 2013). The results may be used to screen the candidates and employ possibly less effort-averse and optimally (with respect to existing organizational structure) risk-averse employees as risk managers, in accordance with recommendations of our study.

### 3.4 Conclusions

Boards of the listed firms are often obliged to implement risk management. However, the literature gives ambiguous recommendations regarding its optimal organizational design. In the agency framework, risk management constitutes a special case of monitoring, where the firm's outcome is used as a performance measure, and risk management is delegated as a task to a risk- and effort-averse manager. As the monitoring literature does not deal with the optimal organizational design in this setting either, our paper aims to fill this gap.

Within our model, we present two alternative structures, coinciding with legal recommendations, in which risk management is treated as any other delegated task. Centralized risk management, with the RM employed directly by the board, corresponds with board-level committees. Decentralized risk management, with the RM employed by the BUM, corresponds with the internal RMSs and/or CROs. We find that organizational structure determines the relation of risk-management and productive activity to one another. This managerial incentives' tradeoff emerges as a crucial factor for the firm's expected profit, with centralization not optimal under the given assumptions, because the marginal risk-management incentives

available for contracting allow only for centralized risk management. This could explain, why we observe centralization in practice, even though the decentralization seems to prevail with respect to the firm's expected profit when both structures are available.

required for each additional unit of productive incentives are higher than in decentralization. This effect originates directly from the organizational structure, as the BUM in decentralization can additionally share the risk she/he is exposed to with RM, her/his lower-tier agent, which necessitates only lower risk-management effort and thus incentives from BUM's point of view. Furthermore, we confirm Friedman's (2016) result on risk aversion as an additional motivation for risk-management activities; Increases in risk aversion may lead to higher risk-management effort when the cost is not too high. In these cases, the more risk-averse managers are, the lower the firm's final risk. We observe it not only in centralization, with similar design to Friedman's (2016) model, but also in decentralization. Thus, we conclude, risk aversion effect is an inherent characteristic of risk-management activity, independent of its organizational design. Overall, with high risk-management effort cost, we see a firm's lower final risk with decentralization rather than with centralization; with low risk-management effort cost, the opposite is true. When the cost of risk-management effort is high, the available combination of managerial incentives allows only for low risk-management effort. When this cost is low, higher risk-management incentives are available. Nonetheless, as the additional risk-sharing is not available under centralization, higher risk-management incentives are required in equilibrium. This leads to lower productive incentives than in decentralization, independently of the cost of risk-management effort. Overall, we observe that lower risk for the firm does not necessarily imply the highest expected profit. The optimal organizational design of risk management implicitly supposes that the firm may remain subject to a certain amount of risk in order not to compromise productive incentives; in equilibrium, an optimal mix of profit and risk for given structure is achieved.

Thus, we mildly support the benefits of internal RMS and/or CROs against the risk management by the board-level committees only, at least with respect to firm's expected profit in firms contracting on their outcomes. This accentuates the perceptional shift from risk management as a staff position, as argued by Reavis (1969), to a more recent view of risk management—advocated by Arena et al. (2010), Schiller and Prpich (2014), and Siegel (2018)—as organized in single hierarchical tiers. The effects on profit and risk observed in these two "pure" organizational designs allow for an intuition behind their simultaneous use that is usually found in practice. Parallel use of both structures may allow for optimal mix of intended effects; Internal RMSs allow for locally optimal relation of risk-management and productive activity, whereas the board-level committees focus stronger on the risk management in broader terms.

Finally, the effects and cross-effects of managerial risk aversion should be reflected in the design of the RMSs, and managerial risk and effort aversion should be considered in recruitment processes.

We examine only a relatively small range of low risk-management effort costs, which constitutes the most serious limitation of this paper. Nonetheless, we believe that our recommendations can generally be accepted, regardless of this limitation, as it can be assumed that the recruitment process should generally favor potential employees characterized by relatively low effort aversion. Furthermore, we assume that the owner and thus the board are risk-neutral. Even though this is a general assumption in many agency models, its implication for our design is obvious—that neither is intrinsically interested in lowering the firm's risk, but only in optimally addressing the legal requirement of providing a RMS.

Further research on risk management design and organizational structures may follow several directions. The validity of the results could be examined for more complex organizational structures like multiple BUMs and RMs or simultaneous use of both structures. The strong and probably far-fetched assumption that managers are compensated based on the firm's outcome could be loosened in favor of a model with non-contractible firms' outcomes. To avoid switching back to the typical monitoring framework, one could assume a correlation between both measures and further introduce different productivities of risk-management effort with regard to the PM's variance and the firm's risk, as well as the risk aversion of the owner (and/or the board). Other possible research areas include risk management in a dynamic context with or without a capital market.

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# 4 Performance measurement in firms with decentralized risk management and risk-averse board

*Marta Michaelis*

ABSTRACT

Risk management is often a legal requirement for listed firms and is a recommended part of corporate governance. It differs from other managerial activities, but its incentivization has not been extensively discussed in literature. To fill this gap, I model a firm under LEN assumptions, with a risk-averse board and a single business unit that employs a risk manager, stylizing a decentralized risk management system. Contracts of the risk-averse managers are based on performance measures correlated with the firm's outcome; risk management decreases the variances of both metrics. Due to the complexity of the results, I propose the use of simulated correlation coefficients as an alternative to comparative statics. The analysis indicates the existence of contradictory effects of the measure's precision: business unit (risk) managers are better incentivized with more (less) precise measures. Still, more precise measures are preferred in contracts, as they attain higher utility in equilibrium, even while reporting higher risk. The results suggest that incentivizing risk managers with the same profit-based measures as other managers may be suboptimal; therefore, diverging or unique contracting metrics must be found for risk managers.

**Keywords:** risk management; incentives; monitoring; performance measurement; simulation

**JEL Classification:** D23; J33; M52

## 4.1 Introduction

Managers that are employed for productive tasks like contracting, coordinating, supporting, and monitoring, impact the general prosperity of the firm and their own compensation (Calvo and Wellisz 1978; Melumad et al. 1995; Hofmann and Indjejikian 2018). Thus, it has always been of utmost importance for firms to measure and accordingly incentivize personnel performance on these tasks. The optimal choice of the number and characteristics of performance measures (PMs) is the core of empirical research by Haubrich (1994), Gibbs et al. (2004), Chenhall and Langfield-Smith (2007), Lazear (2018), and analytical research by Demski (1976), Sappington (1991), Baker (1992), Prendergast (1999), Hofmann and van Lent (2017), and many others. As far as the characteristics of PMs are concerned, their sensitivity and precision are most crucial when a single task is involved. Sensitivity measures how the PM reacts to changes in implemented effort, whereas precision informs of the sole extent to which the PM depends on this effort, without distortion by other factors. The measure of this distortion is a reversed precision, defined as noisiness or the PM's risk. According to analytical research, more precise PMs make incentivizing productive activities of the managers less costly (Banker and Datar 1989; Feltham and Xie 1994).

Among managerial activities, risk management is accorded high importance, especially as risks are becoming increasingly multifaceted (Fatemi and Luft 2002; Simkins and Ramirez 2008; Bromiley et al. 2015). A risk management system is mandatory for firms listed on the stock exchange and generally recommended for all small and medium-sized businesses as an element of corporate governance (OECD 2014). Based on the legal requirements and recommendations for listed firms, risk management is typically the responsibility of the board, taking the form of board-level committees, and/or implementation of internal risk management systems and/or the appointment of Chief Risk Officers (CROs) (OECD 2014; Bennett 2017). CROs are often engaged as risk managers (RMs) for single hierarchical tiers, that is in separate business units by the business unit managers (BUMs), which is tantamount to the decentralization of risk management (Arena et al. 2010; Schiller and Prpich 2014; Siegel 2018). As their efforts fundamentally contribute to the reduction of risks faced by the firm, they influence the decision-making framework of all employees. However, for opportunistic managers, their activities depend on the PMs their contracts are based on. Thus, for the incentivization of RMs, the connection between the risk of the firm and risk of the PM emerges as critical. The role of the PMs' risk and precision need to be re-examined in this context, which constitutes the analytical scope of this study. Supplementarily, I examine the relevance of the board's attitude toward risk within risk management research, discussing additional insights against the enhanced complexity of the results.

Thus, I contribute in three ways to the existing literature. i) I re-evaluate the role of PMs in contracts, focusing on managers responsible for firm's risk, with BUMs (RMs) better incentivized by more (less) precise measures. The evaluation indicates potential non-optimality of incentivizing diverging activities with identical PMs. This is because, even though the obtained equilibrium is identified by the highest utility, it is also characterized by the highest risk. ii) I show that the board's risk aversion creates unambiguous motivation for organizing risk management and is crucial for models implementing PMs diverging from the firm's outcome. Otherwise, the assumption of risk neutrality is generally sufficient to observe other effects relevant for risk-management research. This finding may influence future managerial research focused on risk management. iii) Finally, I take a novel approach to interpreting complex results where analysis of the comparative statics is not possible—in the form of simulated Spearman's rank correlation coefficients as indicators for dependencies between the input and output parameters of the model. This enables new access to the more complex problems within managerial research.

Agency theory is a primary tool for analyzing the influence of PMs' characteristics on managerial incentives. Risk reduction under this framework is usually restricted to increasing the precision of PMs through monitoring, and managing managerial compensation risk, especially in situations where the firm's outcome is not available for contracting (e.g., Fischer 2000; Liang et al. 2008). This should lead to more precise performance measurement and, thus, enhance the efforts of agents. Risk management may be regarded as a special case of monitoring, with a core difference that for RMs, gaining better insight into agents' efforts should not be an aim, but rather a spillover of the activities focused on dealing optimally with the firm's risk. Articles modelling risk- and effort-averse monitors do not usually discuss the relevance of PMs for their behavior, focusing mostly on different problems, such as optimal team size (Liang et al. 2008), optimal task assignment (Schmid 2018) or managerial span of control (Hofmann and Indjejikian 2018) in the presence of monitoring. Overall, the articles mentioned, regard the aim of monitoring activities as solely to influence employees' efforts. None of them provides a link to the firm's outcome or risk, thus disallowing interpretation of the monitoring as risk management, nor discusses the principal's risk aversion as the source of her/his intrinsic interest in risk management. Finally, they do not discuss performance measurement in the context of incentives for RMs.

Closest to the focus of this study are Dürr et al. (2020), who are the authors of perhaps the only monitoring paper modelling a risk-averse principal and underlining this risk aversion as the source of interest in decreasing risk. They extend the model of Liang et al. (2008)—who interpreted the monitors as accountants or auditors, not RMs—and let the productivity of the workers be uncertain. The project manager in the model is employed centrally by the principal and implements two types of effort. One effort decreases the noise of the performance measure and thus, is the same as monitoring. The other effort decreases the uncertainty of the workers' productivity, synonymous to market research. As uncertain productivity is different from the risk of the firm and both sources of risk (variance of the firm's outcome and variance of the PM) do not correlate, the second activity of the manager is not quite the same as risk management. Even if such an interpretation could be accepted, the issues of performance measurement and incentivization of an RM in the absence of a contractible firm's outcome—and thus without a direct link to the firm's risk—are not discussed.

I place the model within the LEN framework, with LEN denoting linear contracts, exponential utility functions, and normally distributed results (Holmström and Milgrom 1987, 1991; Spremann 1987). Managerial research widely accepts the assumption of linear contracts, due to the benefits of the results' tractability within the LEN modeling framework, even though this systematically excludes some optimal, non-linear contracts. I choose to model the contracts of all managers as linear as well, in accordance with contracting practice in the real world, as well as modeling practices in managerial research. I assume that the board of directors represents the shareholders' interests perfectly and thus acts as the principal, maximizing the firm's utility. The board hires one agent, defined as a BUM, who has to engage in productive activity within a single business unit, representing a potential structure with multiple business units. Furthermore, the board requires the BUM to employ an RM to lead an internal risk management system. This corresponds with decentralization of risk management in the working paper of Michaelis and Dierkes (2020), where a decentralized structure leads to less marginal risk-management incentives necessary for additional units of productive incentives, making decentralization more profitable than centralization with respect to the firm's expected profit. Due to the arguments of Michaelis and Dierkes (2020), I restrict the analysis only to this organizational structure.

Managers are risk-averse and the issues of optimal team and firm size or multiple agents and activities are not considered (only two agents—a BUM and an RM—are employed). Furthermore, I assume the board to be risk-averse as well, as the principals have originally been modeled as such in an agency (Mirrlees 1976; Rogerson 1985; Spremann 1987). This assumption has since been dropped in favor of a risk-neutral principal (Holmström and Milgrom 1987, 1991 and many more), especially in monitoring literature (Liang et al. 2008; Friedman 2016; Hofmann and Indjejikian 2018) mostly due to the enhanced complexity of the results. Nonetheless, assuming risk aversion of the shareholders—and thus of the board representing them—constitutes their intrinsic interest in diminishing risk besides the legal requirements and comply-or-explain rules (OECD 2014). It is also in line with the presumed risk aversion of the individuals in general (Holt and Laury 2002; Eckel and Grossman 2008). Moreover, this assumption is especially relevant if the projects within firms are not easily diversifiable, the firm is family-run and thus rather inflexible and finally, when the shareholders are dominated by one central block holder (Dürr et al. 2020).

I assume that the firm's outcome is not contractible. As the RM is always opportunistic in her/his decisions, the only possibility to incentivize risk management is to find a PM, whose variance is positively correlated with the variance of the firm's outcome, so that the risk-management effort affects both. This is in line with empirical findings, denoting that the managerial contracts of CEOs and oversight managers are based on stock and options (Sanders 1999; Aggarwal and Samwick 2003) or on the profit-based measures (Gibbs et al. 2004). For these PMs, decreasing the firm's risk implies a decrease in their volatility to a certain extent. Furthermore, basing an RM's contract directly on a variance or similar risk metric would be problematic from a legal point of view and could be met with acceptance problems as well. Even though the RM's performance is sometimes assessed based on the necessity to correct the financial statements, this is mostly used for inducing truthful reporting, rather than for incentivizing managerial effort. In this way, the RM's activity, even when employed for monitoring, can be interpreted as risk-management, simultaneously increasing the PM's precision (e.g., Hofmann and Indjejikian 2018) and reducing the firm's risk. However, the extent to which it holds true depends on whether the firm's risk has any relevance for managerial contract.

Ignoring the moral hazard problem, I begin with the analysis of optimal risk-sharing. The risk-averse board optimizes the risk it is exposed to by enforcing a risk-management effort and sharing the remaining risk with their managers. When efforts are observable, risk-management effort in equilibrium is determined by the firm's original risk, but is also influenced by the original precision of the PM and the correlation between the contracting metric and firm's outcome, as these influence risk-sharing possibilities. Thus, even without moral hazard, less precise measures lead to less final risk, whereas more precise measures induce higher utility.

Reintroducing the moral hazard problem enhances the complexity of the results. Thus, I discuss the second-best problem for a risk-neutral board first, as a benchmark for the analysis of the relevance of the principal's risk attitude within managerial research on risk management. I observe (extended) risk aversion effects, in a model like the one by Michaelis and Dierkes (2020): the risk aversion of the RM motivates her/him to exert more effort, whereas the risk aversion of the BUM motivates her/him to incentivize more risk-management effort. Overall, the increase in managerial risk aversion may positively influence risk-management effort, if the cost of this effort is not too high, but it always exerts a negative influence on the BUM's effort and thus on the firm's expected utility. Other than that, the assumption of the principal's risk-neutrality severs all connections between the activity of the RM and the firm's final risk, other than an accidental spillover effect. The original risk of the firm, and the correlation between the firm's outcome and the contracting metric, have no relevance for the results.

For the second-best problem with a risk-averse board, I construct an agent-based model to predict the influence of the input parameters on the results (Harrison et al. 2007). I simplify the simulation design, by computing and then simulating the analytical results, based on uniformly distributed input parameters in a multitude of trials. In this manner, using a simulation add-in for Excel, Oracle Crystal Ball, I obtain the outliers-robust Spearman's rank correlation coefficients. The simulation does not allow for an as unambiguous interpretation as the formal analysis in case of the board's risk neutrality, but indicates the existence of similar effects. The board's risk aversion constitutes its interest in organizing risk management. Still, contracting on the PM makes from the risk management activity a monitoring activity per design, for which risk management emerges only as a spillover. However, contrary to the case of the board's risk-neutrality, this spillover is not accidental, as the firm's risk is still relevant to the results, including managerial incentives. The contradictory effects of the PM's precision on managerial incentives indicate that diverging PMs must be used for different managerial activities and that the results obtained for productive managers cannot be fully transferred to RMs.

The remainder of this paper is organized as follows. The theoretical framework is provided in Chapter 4.2, beginning with a detailed model design and the derivation, and a discussion of the first-best results. Furthermore, I reintroduce the incentive problem and derive the second-best results in Chapter 4.3, analyzing them for the special case of a risk-neutral board, to establish a benchmark for the case of a risk-averse board. Finally, in Chapter 4.4, I discuss simulation as a research method and present a discussion of the simulation results. This paper closes with the conclusion in Chapter 4.5.

## 4.2 Theoretical framework and the risk-sharing problem

### 4.2.1 Model design

I consider an organization with a risk-averse board of directors and a risk-averse BUM, in a single-period setting. The board, representing the owner perfectly, delegates to the BUM a productive activity, and the authority to contract with a risk-averse RM to fulfill the legal requirements of the implementation of an internal risk management system. The BUM does not pay the RM out of her/his own pocket, but rather determines and pays the wages of the RM from the compensation pool provided for her/him by the board, as discussed by Hofmann and Indjejikian (2018).

Engaging in productive activity with an effort $e$ results in a cost of effort $0.5 \cdot e^2$ and influences the firm's outcome $x$:

$$\tilde{x} = e + \tilde{\varepsilon}_x \text{ with } \tilde{\varepsilon}_x \sim N\left(0, \frac{\sigma_x^2}{m}\right) \text{ and thus } pr_x = \frac{1}{\sigma_x^2}. \tag{28}$$

As the firm's outcome is often non-verifiable or is realizable too far in the future, it may not be available for contracting. Then, the contracts must be based on the PM $y$, whose precision diverges from the precision of the firm's outcome, indicating the different risks of both metrics:

$$\tilde{y} = e + \tilde{\varepsilon}_y \text{ with } \tilde{\varepsilon}_y \sim N\left(0, \frac{\sigma_y^2}{m}\right) \text{ and thus } pr_y = \frac{1}{\sigma_y^2}. \tag{29}$$

The original precision of the metrics, before the risk-management effort is chosen in equilibrium, are defined by $pr_x$ and $pr_y$, with their reciprocals as the original risks of the metrics. In particular, the parameter $\sigma_x^2$ is the original risk of the firm that is to be managed. To this aim, the RM should engage in risk management with effort level $m \geq 0$ and private costs $k \cdot m$ with $k$ given as the cost of the risk-management effort. Managers are identical in all respects, including the potential cost of the risk-management effort, with the only difference between them being the grade of their risk aversion. The cost functions are inherent to the activities, not to the managers, with the convex function for cost of productive effort and linear function for cost of the risk-management effort chosen for tractability. Other functions which are increasing and concave in m would also be suitable to model cost of the risk-management effort, but would lead to higher results' complexity (see Liang et al. 2008).

Modeling risk-management activities explicitly as variance-reducing effort, is in line with understanding risk as variances in results, as found in the literature (Prendergast 2002; Arena et al. 2010). However, as contracts are based on the PM, the managerial decision regarding their effort occurs primarily with respect to the variance of this measure, $\sigma_y^2$. Overall, the firm's final risk after risk management, defined in (28) as the effective variance of the exogenous noise of the firm's outcome, is determined by RM's endogenous choice of *m* in equilibrium. The same is true for the final variance of the performance measure defined in (29). As the focus lies on the risk of the firm and, thus, on the contracting metrics' variances, the metrics have per design the same sensitivity, identical with the marginal productivity of BUM's effort of 1. Therefore, I do not further discus this characteristic. Furthermore, I assume that the productivity of the risk-management effort is the same with respect to the firm's and PM's original risks as well. Introducing additional parameters to account for diverging productivity of this effort is possible, but it increases the results' complexity without providing additional insights. Finally, the PM and firm's outcome are non-negatively correlated, following covariance in equilibrium:

$$Cov\left[\tilde{y},\tilde{x}\right]=\frac{\rho\cdot\sigma_y\cdot\sigma_x}{m} \text{ with } \rho\in\left[0;1\right]. \tag{30}$$

The empirical evidence points toward a correlation between the managerial pay and firm's performance (Lewellen and Huntsman 1970; Prendergast 1999), allowing an assumption that the managerial and firm's performance are positively correlated as well. The covariance in (30) results directly from mathematical derivation based on the variances of *x* and *y* as defined in (28) and (29). Managerial contracts are specified as

$$v_B\left(\tilde{y}\right)=a_B\cdot\tilde{y}+b_B \tag{31}$$

for BUM and

$$v_R\left(\tilde{y}\right)=a_R\cdot\tilde{y}+b_R \tag{32}$$

for RM. The parameter *b* represents the base salary of managerial compensation, whereas the parameter *a* indicates the variable share of managerial compensation, based on a PM. Thus, the risk-management effort simultaneously decreases the risk faced by the firm and the uncertainty of managers' compensation. Furthermore, the efforts are not directly observable or verifiable and I exclude the possibility of side-contracting between the managers. All parties are effort- and risk-averse with a constant absolute risk aversion ($r_B$, $r_R$, and $r_P$ respectively) and all outside options are normalized to 0. I summarize the key notations in Table 4.

| variables | |
|---|---|
| $a_i$ | variable share of compensation of the manager $i \in \{B, R\}$ |
| $b_i$ | base salary of the manager $i \in \{B, R\}$ |
| $CE_i$ | certainty equivalent of the party $i \in \{B, P, R\}$ |
| $e$ | productive effort |
| $E$ | all available productive efforts |
| $H$, $J$ | auxiliary variables |
| $IC_i$ | incentive compatibility constraint of the manager $i \in \{B, R\}$ |
| $k$ | risk-management effort cost |
| $m$ | risk-management effort |
| $M$ | all available risk-management efforts |
| $PC_i$ | participation constraint of the manager $i \in \{B, R\}$ |
| $pr_i$ | original precision of the metric $i \in \{x, y\}$ |
| $pr_{PM}$ | precision of the PM $y$ after risk-management effort is chosen in equilibrium |
| $r_i$ | constant absolute risk aversion parameter of the party $i \in \{B, P, R\}$ |
| $v_i$ | contract of the manager $i \in \{B, R\}$ |
| $x$ | firm's outcome |
| $y$ | performance measure |
| $\tilde{\varepsilon}_i$ | uncontrollable events of the metric $i \in \{x, y\}$ |
| $\Delta$, $\Delta_k$ | discriminant |
| $\rho$ | correlation between the firm's outcome and the performance measure |
| $\sigma_i^2$ | original variance (risk) of the metric $i \in \{x, y\}$ |
| $\sigma_F^2$ $\left(\sigma_{PM}^2\right)$ | final risk of the firm (of the PM) after risk-management effort is chosen in equilibrium |
| $\omega$ | restriction on risk-management effort cost |
| **sub-/ superscripts** | |
| $B$, $P$, $R$ | business unit manager; risk manager; principal i.e. board, owner |
| $FB$, $SB$ | first-best, second-best |
| $r_P = 0$ | in case of board's risk neutrality |

**Tab. 4 Summary of key notations.**

### 4.2.2 First-best solution in case of the board's risk aversion

First, the concept of the first-best solution in a structure with delegated contracting authority must be established. The decentralized organization of risk management within the firm is given, but without moral hazard all efforts are observable. Thus, the board is able not only to enforce productive effort, but also to expect that the BUM enforces risk-management effort that is optimal from the board's perspective. This means that the board enforces both managerial efforts and variable shares and the BUM has no decision power.

In all cases, the certainty equivalents of the managers must be granted, in order to fulfill the participation constraints. The RM's certainty equivalent is characterized by:

$$CE_R = E\left[v_R\left(\tilde{y}\right)\right] - k \cdot m - \frac{1}{2} \cdot r_R \cdot Var\left[v_R\left(\tilde{y}\right)\right]. \quad (33)$$

Further, the BUM's certainty equivalent is characterized by:

$$CE_B = E\left[v_B\left(\tilde{y}\right) - v_R\left(\tilde{y}\right)\right] - \frac{1}{2} \cdot e^2 - \frac{1}{2} \cdot r_B \cdot Var\left[v_B\left(\tilde{y}\right) - v_R\left(\tilde{y}\right)\right]. \quad (34)$$

The risk-averse board maximizes its certainty equivalent to determine the optimal productive and risk-management efforts and the necessary variable shares in the following way:

$$\max_{e,m,a_B,a_R} CE_P = E\left[\tilde{x} - v_B\left(\tilde{y}\right)\right] - \frac{1}{2} \cdot r_P \cdot Var\left[\tilde{x} - v_B\left(\tilde{y}\right)\right] \quad (35)$$

$$\text{s.t. } PC_B : CE_B\left(e^{FB}\right) \geq 0 \quad (36)$$

$$PC_R : CE_R\left(m^{FB}\right) \geq 0 \ . \quad (37)$$

In Proposition 4 below, the overview of the first-best results is presented. For the risk-management effort to be profitable, it must be greater than 1, generating a necessary restriction to the cost of the risk-management effort. Derivation of these relevant bounds can be found in Appendix A11.

**Proposition 4** When contracts are based on a PM correlated with the firm's outcome, the following first-best variable share and effort of the BUM are obtained:

$$a_B^{FB} = \frac{r_R \cdot r_P \cdot \rho}{2 \cdot r_B \cdot r_R + r_P \cdot r_R - r_B^2} \cdot \sqrt{\frac{pr_y}{pr_x}} \text{ and } e^{FB} = 1 \quad (38)$$

with the first-best variable share and effort of the RM,

$$a_R^{FB} = \frac{r_B}{r_R} \cdot a_B^{FB} \text{ and } m^{FB} = \sqrt{\left(1 - \frac{r_R \cdot r_P \cdot \rho^2}{2 \cdot r_B \cdot r_R + r_P \cdot r_R - r_B^2}\right) \cdot \frac{r_P}{2 \cdot k \cdot pr_x}}, \quad (39)$$

the firm's expected utility:

$$CE_P^{FB} = \frac{1}{2} - \sqrt{\left(1 - \frac{r_R \cdot r_P \cdot \rho^2}{2 \cdot r_B \cdot r_R + r_P \cdot r_R - r_B^2}\right) \cdot \frac{2 \cdot k \cdot r_P}{pr_x}}, \quad (40)$$

and the firm's final risk, and final precision of the PM in equilibrium:

$$\sigma_{F,FB}^2 = \frac{1}{pr_x \cdot m^{FB}} \text{ and } pr_{PM,FB} = pr_y \cdot m^{FB}. \quad (41)$$

The foundation for the analysis is the comparative statics, which can be found in Table 5. As the efforts are observable, risk-management is enforced with regard to the firm's original risk. Thus, a change in the PM's precision does not influence the first-best efforts, firm's expected utility, or firm's final risk. The main effect observed is, that an increase in the firm's original risk leads to more risk transfer to the managers, visible in higher variable shares. It also leads to enforcement of higher risk-management effort, constituting the board's risk aversion as motivation for organizing risk management systems. More risk-management effort leads in all cases, per spillover, to an increase in the final precision of the PM.

| | **BUM** | **firm** | **RM** | | **risk measures** | |
|---|---|---|---|---|---|---|
| | $\partial a_B$ | $\partial CE_P$ | $\partial m$ | $\partial a_R$ | $\partial \sigma_F^2$ | $\partial \sigma_{PM}^2$ |
| $/\partial k$ | - | $< 0$ | $< 0$ | - | $> 0$ | $> 0$ |
| $/\partial \sigma_x^2$ | $> 0$ | $< 0$ | $> 0$ | $> 0$ | $> 0$ | $< 0$ |
| $/\partial pr_x$ | $< 0$ | $> 0$ | $< 0$ | $< 0$ | $< 0$ | $> 0$ |
| $/\partial \sigma_y^2$ | $< 0$ | - | - | $< 0$ | - | $> 0$ |
| $/\partial pr_y$ | $> 0$ | - | - | $> 0$ | - | $< 0$ |
| $/\partial \rho$ | $> 0$ | $> 0$ | $< 0$ | $> 0$ | $> 0$ | $> 0$ |
| $/\partial r_P$ | $> 0 \quad r_R > 0.5 \cdot r_B$<br>$< 0 \quad r_R < 0.5 \cdot r_B$ | $< 0$ | $> 0$ | $> 0 \quad r_R > 0.5 \cdot r_B$<br>$< 0 \quad r_R < 0.5 \cdot r_B$ | $< 0$ | $< 0$ |
| $/\partial r_B$ | $< 0 \quad r_R > r_B$<br>$> 0 \quad r_R < r_B$ | $< 0 \quad r_R > r_B$<br>$> 0 \quad r_R < r_B$ | $> 0 \quad r_R > r_B$<br>$< 0 \quad r_R < r_B$ | $> 0$ | $< 0 \quad r_R > r_B$<br>$> 0 \quad r_R < r_B$ | $< 0 \quad r_R > r_B$<br>$> 0 \quad r_R < r_B$ |
| $/\partial r_R$ | $< 0$ | $< 0$ | $> 0$ | $< 0$ | $< 0$ | $< 0$ |

**Tab. 5 Comparative statics of the first-best solution in case of a risk-averse board.**

Nonetheless, the precision of the PM does indirectly influence the results. More precise PMs indicate less compensation risk of the managers and lead them to be more accepting of risk transfer from the board. This is true when the correlation between the PMs and the firm's outcome increases, due to profit from additional information. This increased risk-sharing lessens the necessity of risk management in the first place, thus leading in equilibrium to higher final risk, which is however accompanied by higher firm's utility. Thus, even without the moral hazard problem, contracting on a less precise PM leads to lower final risk, whereas contracting on a more precise PM enhances utility.

Risk-sharing in the first best case is also influenced by further factors, which are supplementarily discussed here. As far as the influence of risk aversion is concerned, lower shares are generally offered to the more risk-averse managers, as they only accept less risk. An increase in the RM's risk aversion always leads to lower variable shares of both managers. The board enforces more risk-management effort, obtaining in equilibrium lower final risk and lower expected utility.

For an increase in the BUM's risk aversion, I consider two cases. Overall, when her/his risk aversion increases, the risk is transferred to the RM, increasing the RM's variable share. Moreover, when the RM is less risk-averse than the BUM, the board is interested in transferring even more risk to such an RM. To this aim, due to the hierarchical structure, it offers a higher variable share to the BUM, which further enhances the RM's share. In such a case, the board does not need to induce much risk-management effort in the optimum, leading to the firm's higher final risk, but also higher expected utility. When the RM is more risk-averse than the BUM, the former's share increases, but the latter's does not, as the BUM transfers more risk down the hierarchical tiers and simultaneously accepts less risk to begin with. Then, the board enforces more risk-management effort, leading to lower final risk and lower utility in equilibrium.

Finally, an increase in the board's risk aversion leads, in all cases, to the enforcement of higher risk management effort, thus lowering the firm's and PM's final risks, and the firm's expected utility. Regarding risk-sharing, differentiation is necessary once again. As long as the BUM is no more than twice as risk-averse as the RM, the increase in the board's risk aversion leads to higher managerial variable shares, as more risk is transferred from the board to the managers, who, in sum, are not very risk-averse. However, when the BUM is more than twice as risk-averse as the RM, the board is unable to provide the required variable shares. Thus, the managerial shares decrease with the board's risk aversion, as the board must accept more risk even though it is also more risk-averse.

Overall, the board has two possible ways to deal with the risk it faces—in the form of risk-sharing with managers and enforcing risk-management effort. The risk-management effort is, however, less preferable, as it negatively influences utility due to increased effort costs of the RM. In equilibrium, an optimal mix of utility and risk emerges, with lower risk available only at lower utility and higher risk allowing for higher utility.

## 4.3 Analytical approach to the risk-sharing and incentive problems

### 4.3.1 Second-best solution in case of the board's risk aversion

In the second-best problem, the BUM optimizes her/his certainty equivalent, subject to the RM's participation and incentive constraints. Thus, I denote her/his problem as follows:

$$\max_{e,a_R} CE_B = E\left[v_B(\tilde{y}) - v_R(\tilde{y})\right] - \frac{1}{2}\cdot e^2 - \frac{1}{2}\cdot r_B \cdot Var\left[v_B(\tilde{y}) - v_R(\tilde{y})\right] \tag{42}$$

$$\text{s.t. } PC_R : CE_R\left(m^{SB}\right) \geq 0 \tag{43}$$

$$IC_R : m^{SB} \in \arg\max_{m^{SB}\in M}\left\{CE_R\left(m^{SB}\right)\right\}. \tag{44}$$

Furthermore, the board must account for the BUM's participation and incentive constraints with the problem represented accordingly:

$$\max_{a_B} CE_P = E\left[\tilde{x} - v_B(\tilde{y})\right] - \frac{1}{2}\cdot r_P \cdot Var\left[\tilde{x} - v_B(\tilde{y})\right] \tag{45}$$

$$\text{s.t. } PC_B : CE_B\left(e^{SB}\right) \geq 0 \tag{46}$$

$$IC_B : e^{SB} \in \arg\max_{e^{SB}\in E}\left\{CE_B\left(e^{SB}\right)\right\}\ . \tag{47}$$

The results are summarized in Proposition 5, with the derivation provided in Appendix A12. In this case the parameter restrictions are necessary as well. I define and analyze these in Appendix A13.

**Proposition 5** When contracts are based on a PM correlated with the firm's outcome, the following second-best variable shares (productive incentives) and effort of the BUM are obtained:

$$a_B = \frac{1}{12\cdot H}\cdot\left(1 + \sqrt[3]{1 + \frac{J}{2\cdot H^3}\cdot\left(1 + \sqrt{1 + \frac{4\cdot H^3}{J}}\right)} + \sqrt[3]{1 + \frac{J}{2\cdot H^3}\cdot\left(1 - \sqrt{1 + \frac{4\cdot H^3}{J}}\right)}\right) \tag{48}$$

and $e^{SB} = a_B^{SB}$, (49)

with

$$J = 27\cdot\sqrt{\frac{pr_y\cdot k\cdot\left(2\cdot r_R + r_B\right)}{2\cdot r_B\cdot r_R}}\cdot\frac{r_P}{pr_x}, \tag{50}$$

$$H = \left(1 - \left(\left(2\cdot r_B + r_P\right)\cdot\sqrt{\frac{2\cdot r_R + r_B}{r_B}} - 2\cdot r_B\right)\cdot\sqrt{\frac{k}{2\cdot pr_y\cdot r_R}}\right). \tag{51}$$

Moreover, the second-best variable shares (risk-management incentives) and effort of the RM are:

$$a_R^{SB} = a_B^{SB} \cdot \sqrt{\frac{r_B}{2 \cdot r_R + r_B}} \text{ and } m^{SB} = a_R^{SB} \cdot \sqrt{\frac{r_R}{2 \cdot pr_y \cdot k}}, \tag{52}$$

and the firm's expected utility, firm's final risk, and final precision of the PM in equilibrium are:

$$CE_P^{SB} = H \cdot a_B^{SB} - \frac{1}{2} \cdot \left(a_B^{SB}\right)^2 - \frac{J}{27} \cdot \left(\frac{1}{a_B^{SB}} - 2 \cdot \rho \cdot \sqrt{\frac{pr_x}{pr_y}}\right), \tag{53}$$

$$\sigma_{F,SB}^2 = \frac{1}{pr_x \cdot m^{SB}} \text{ and } pr_{PM,SB} = pr_y \cdot m^{SB}. \tag{54}$$

### 4.3.2 Second-best solution in case of the board's risk neutrality

As the results of the problem in the previous section are too complex to analyze, I discuss the case of a risk-neutral board first, with detailed results provided in Appendix A14, and the relevant bounds derived in Appendix A15. Comparative statics for the case of a risk-neutral board can be found in Table 6. The results obtained are like those of Michaelis and Dierkes (2020), but with PM *y* used in the contracts instead of the firm's outcome. They constitute the benchmark case for the analysis of the relevance of the risk attitude of the board—or, more broadly, the principal—for managerial research in risk management.

The risk aversion of the RM as a motivational factor plays a decisive role in this framework, as it impels her/him toward additional effort (the risk aversion effect), decreasing the firm's final risk. Moreover, the increase of the BUM's risk aversion influences the RM as well, due to the extended risk aversion effect. This is because a more risk-averse BUM imposes stronger incentives and, thus, induces more effort by the RM to lessen the risk she/he is exposed to, if it is profitable due to sufficiently low cost of the risk-management effort. The managerial incentives intertwine and for each additional unit of productive incentives, additional risk-management incentives must be provided, with the amount defined by managerial risk aversion. Thus, an increase in the risk aversion of any of the managers changes the tradeoff between managerial incentives. Requiring more risk-management incentives impairs productive incentives and thus decreases the productive effort, and the firm's expected utility (identical with the firm's expected profit in the risk-neutral case).

An increase in the original precision of the PM leads to higher incentives of the managers, higher effort of the BUM, and higher firm's expected utility, as is usual within agency models. However, as the RM's effort is determined not only by her/his incentives but also by her/his risk aversion, the increase in the precision of a PM decreases the motivation of the RM, as the risk is lower to begin with, like with the risk aversion effect. The overall effect on the risk-management effort is determined by the cost of this effort as well. When the original risk of the PM increases, the RM is ready to increase her/his effort, as long its cost is not too high; but this effect is not present in the case of higher cost of the risk-management effort.

| | **firm BUM** | **RM** | | **risk measures** | |
|---|---|---|---|---|---|
| | $\partial CE_P$<br>$\partial a_B$<br>$\partial e$ | $\partial m$ | $\partial a_R$ | $\partial \sigma_F^2$ | $\partial \sigma_{PM}^2$ |
| $/\partial k$ | $< 0$ | $< 0$ | $< 0$ | $> 0$ | $> 0$ |
| $/\partial \sigma_x^2$ | - | - | - | $> 0$ | - |
| $/\partial pr_x$ | - | - | - | $< 0$ | - |
| $/\partial \sigma_y^2$ | $< 0$ | $> 0\ \forall k;\ \sqrt{k} \in \left(0;\ \omega_2^{r_P=0}\right)$<br>$< 0\ \forall k;\ \sqrt{k} \in \left(\omega_2^{r_P=0};\ \omega_0^{r_P=0}\right)$ | $< 0$ | $> 0\ \forall k;\ \sqrt{k} \in \left(0;\ \omega_2^{r_P=0}\right)$<br>$< 0\ \forall k;\ \sqrt{k} \in \left(\omega_2^{r_P=0};\ \omega_0^{r_P=0}\right)$ | $> 0$ |
| $/\partial pr_y$ | $> 0$ | $< 0\ \forall k;\ \sqrt{k} \in \left(0;\ \omega_2^{r_P=0}\right)$<br>$> 0\ \forall k;\ \sqrt{k} \in \left(\omega_2^{r_P=0};\ \omega_0^{r_P=0}\right)$ | $> 0$ | $> 0\ \forall k;\ \sqrt{k} \in \left(0;\ \omega_2^{r_P=0}\right)$<br>$< 0\ \forall k;\ \sqrt{k} \in \left(\omega_2^{r_P=0};\ \omega_0^{r_P=0}\right)$ | $< 0$ |
| $/\partial r_B$ | $< 0$ | $> 0\ \forall k;\ \sqrt{k} \in \left(0;\ \min\left\{\omega_0^{r_P=0};\ \omega_3^{r_P=0}\right\}\right)$<br>$< 0\ \forall k;\ \sqrt{k} \in \left(\min\left\{\omega_0^{r_P=0};\ \omega_3^{r_P=0}\right\};\ \omega_0^{r_P=0}\right)$ | $> 0\ \forall k;\ \sqrt{k} \in \left(0;\ \min\left\{\omega_0^{r_P=0};\ \omega_1^{r_P=0}\right\}\right)$<br>$< 0\ \forall k;\ \sqrt{k} \in \left(\min\left\{\omega_0^{r_P=0};\ \omega_1^{r_P=0}\right\};\ \omega_0^{r_P=0}\right)$ | $< 0\ \forall k;\ \sqrt{k} \in \left(0;\ \min\left\{\omega_0^{r_P=0};\ \omega_3^{r_P=0}\right\}\right)$<br>$> 0\ \forall k;\ \sqrt{k} \in \left(\min\left\{\omega_0^{r_P=0};\ \omega_3^{r_P=0}\right\};\ \omega_0^{r_P=0}\right)$ | $< 0\ \forall k;\ \sqrt{k} \in \left(0;\ \min\left\{\omega_0^{r_P=0};\ \omega_3^{r_P=0}\right\}\right)$<br>$> 0\ \forall k;\ \sqrt{k} \in \left(\min\left\{\omega_0^{r_P=0};\ \omega_3^{r_P=0}\right\};\ \omega_0^{r_P=0}\right)$ |
| $/\partial r_R$ | $< 0$ | $> 0$ | $> 0\ \forall k;\ \sqrt{k} \in \left(0;\ \min\left\{\omega_0^{r_P=0};\ \omega_4^{r_P=0}\right\}\right)$<br>$< 0\ \forall k;\ \sqrt{k} \in \left(\min\left\{\omega_0^{r_P=0};\ \omega_4^{r_P=0}\right\};\ \omega_0^{r_P=0}\right)$ | $< 0$ | $< 0$ |

**Tab. 6 Comparative statics of the second-best solution in case of a risk-neutral board.** The additional restrictions in the form of parameters ω are provided in the Appendix A16.

Therefore, contracting on a metric other than the firm's outcome in the presence of a risk-neutral board means that the firm's original risk loses almost all its relevance for the results. This is because there exists no connection between the contracts and the firm's expected utility due to the absence of the board's risk premium. The correlation of the metrics is irrelevant as well. Therefore, in this framework, risk management is truly an accidental effect of the monitoring activity of the RM, directed only at optimizing the variance of the PM on which the contracts are based. Managerial risk aversion negatively influences the firm's expected utility and has a mixed influence on the firm's final risk—generally decreasing it, while the cost of the risk-management effort is sufficiently low. Overall, the equilibrium is always obtained with regard to the risk of the PM and not the risk of the firm.

## 4.4 Simulation-based approach to the risk-sharing and incentive problems

### 4.4.1 Use of simulation in managerial accounting and simulation setting

Relaxing the risk-neutrality assumption leads back to the second-best results as seen in Proposition 5. These, however, are characterized by high complexity, due to which the analysis and even the derivation of the comparative statics are barely possible. Thus, other methods of analysis must be implemented, such as simulation.

As a research method, simulation began to slowly acquire popularity around 1990, first within the social sciences, and later, in organizational and management research as well (Harrison et al. 2007). The use of simulation within managerial research is, in its broadest, summarized as agent-based computational economics. It is well-grounded in research on economies as evolving systems, making use of new and powerful computational tools such as suitable programming languages and enhanced computing power. The agent-based models can also be used to simulate organizational structures and within them, diverse specifics of the agents, along with evolutionary processes and learning over time and tasks (Tesfatsion 2001; Chang and Harrington 2006).

A few overview articles discuss the general issues of implementing simulations in managerial and accounting sciences. Harrison et al. (2007) postulate a stronger understanding of the simulation methodology to promote it as a tool. They name the failing tractability of mathematical derivations as the main problem of more complex analytical models. Conversely, data availability restricts the implementation of empirical methods in certain cases. Thus, in the form of a virtual experiment, a simulation allows insight into the core mechanisms of more complex models when a mathematical analysis reaches its limits. For Harrison et al. (2007), simulation is a formal model that is dealt with computationally and not analytically. With Harrison et al. (2007) as a starting point, the later overview articles of Labro (2015), Leitner and Wall (2015), and Wall (2016), point toward the potential of simulations as a tool for research questions that are too difficult to solve with other methods. Difficulties of the method, such as external validity and general acceptance, are discussed as well.

The aforementioned articles discuss problems that are not easily computable and have high complexity on the level of input parameters and system processes. The constructed models are simulated multiple times so that the achieved results can be interpreted further. In this study, however, the second-best problem with a risk-averse board is computable, as seen in the previous sections, but the results obtained are not easily interpretable. In this case, a much simpler approach toward simulation is sufficient to gain insight into the mechanics of the modeled problem. The first step of the simulation process, as postulated by Harrison et al. (2007), is the set of equations, according to which the system functions. Instead of simulating the whole system, I dealt with this part analytically and computed the results directly in order to further simulate them with the Monte Carlo method. From these, I obtain correlations between each output and input parameter. This allows for a better understanding of the influence of these parameters on the results, in a manner similar to the comparative statics, albeit not as uncontestable (Kruskal 1958; Harrison et al. 2007).

As far as correlations are concerned, there are diverse coefficients that can be computed. The most popular is the Pearson product-moment correlation coefficient and, within the class of rank correlations, the Spearman's rank correlation coefficient (the other most relevant being Kendall's Tau, and Goodman and Kruskal's Gamma). Pearson measures the linear correlation between the parameters, computed as a covariance between the variables divided by the product of their respective standard deviations. This correlation coefficient can be misleading if outliers are present (Devlin et al. 1975; Charnes 2012). On the contrary, the rank correlations use a transfer from measurements to ranks, thus generating coefficients that are robust against outliers. In general, rank correlations measure the extent to which an output variable is influenced by change in an input variable. Diverse methods lead mostly to the same interpretations; however, the Spearman's rank correlation is interpreted as the proportion of variability that is accounted for, whereas Tau and Gamma are interpreted on the level of probability (Kruskal 1958; Costner 1965). The Spearman's rank correlation is constructed as a Pearson's correlation coefficient computed from the rank of observations. A positive correlation implies that the parameter has a positive influence on the result; a negative correlation implies the opposite. The value of the correlation coefficient indicates the strength of the linear relationship between the variables or the parameters and the output. Spearman's correlation works well with most distributions (Charnes 2012). Its robustness against outliers makes it especially well-suited for the virtual experiment I conduct in the following sections. Thus, I choose a MS Excel add-in Crystal Ball as a simulation software, as it uses Spearman's rank correlation within its sensitivity analysis. I directly implement Proposition 5 into MS Excel and, thus, obtain a model with optimal results in which the variance from the normal distribution, and correlation between the metrics are accounted for as input parameters.

I further assume uniform distribution for all the inputs, as every parameter value is equally probable. Theoretically, the intervals over which the distributions are spread could be indefinitely wide. Nonetheless, one could argue that, to achieve insight into the basic relationship between the parameters, it is sufficient to depict only a certain small interval. I opted for a [0;1] interval for all the input parameters. For positive correlation it is the only mathematically correct assumption. For risk aversion one could argue, that it could be a percentage of individual aversion toward risk, also proceeding toward the [0;1] interval. Similar interpretation could be implemented toward the cost of the risk-management effort, although in this case a smaller interval could also be chosen, to account for a preference toward RMs with low aversion to effort. Finally, the restriction on the variances is an arbitrary one, as one could propose any other, higher upper bound. Nonetheless, increasing the riskiness of the environment produces less results from the same number of simulations, due to the binding restrictions on the RM's cost of effort and the board's aversion to risk. Thus, changing the upper bound in this case would require increasing the number of simulation trials, without notably changing the results.

For each combination of the parameters, the optimal solution is computed. Running multitudes of trials enables a sensitivity analysis based on rank correlations. However, using the simulation comes at a cost, as the results are not as robust as in the mathematical analysis. The direction and magnitude of the variable's connections are clearly visible from the obtained rank correlations. Contrariwise to the comparative statics, however, the rank simulations may cover up certain insights. Especially when the influence of a parameter differs within certain ranges, only the cumulative result in the form of a single, presumably low rank correlation is visible, showing the predominating influence. Moreover, only sufficiently high rank correlations are suitable for interpretation. I interpret mostly the strong (absolute value above 0.4) and moderate (absolute values of 0.3–0.4) rank correlation coefficients. I also deliver a guarded interpretation of the parameters with weak (absolute values of 0.2–0.3) rank correlation and mostly omit the parameters with lower rank correlation. There is no consensus on the interpretation of certain ranges of correlation coefficients. There are, however, some recommendations—this overview can be found, for example, in Akoglu (2018).

### 4.4.2 Simulation results and a comparison with benchmark settings

Based on the analytical results, I construct the simulation which indicates rank correlations between the input and output parameters, as summarized in Table 7. The efforts are no longer directly observable and due to moral hazard, the incentive problem additionally emerges.

| | **BUM** | **firm** | **RM** | | **risk measures** | |
|---|---|---|---|---|---|---|
| | $a_B=e$ | $CE_P$ | $m$ | $a_R$ | $\sigma_F^2$ | $\sigma_{PM}^2$ |
| $k$ | 0.24* | -0.39** | -0.08 | 0.24* | 0.07 | 0.06 |
| $\sigma_x^2$ | 0.12 | -0.22* | 0.09 | 0.11 | 0.35** | -0.10 |
| $\sigma_y^2$ | 0.09 | -0.09 | 0.37** | 0.10 | -0.32** | 0.19 |
| $\rho$ | 0.00 | 0.12 | 0.00 | 0.00 | -0.00 | -0.00 |
| $r_P$ | 0.22* | -0.44*** | 0.19 | 0.21* | -0.17 | -0.29* |
| $r_B$ | 0.06 | 0.07 | 0.21* | 0.24* | -0.19 | -0.21* |
| $r_R$ | 0.05 | 0.00 | 0.15 | -0.11 | -0.14 | -0.17 |

**Tab. 7 Simulation-based rank correlation coefficients of the second-best solution in case of a risk-averse board** (based on 980,766 observations from 1,000,000 trials). Input parameters are uniformly distributed over the interval [0;1]. The stars characterize the strength of the correlation (with respect to its absolute value): *** strong (≥ 0.4), ** moderate (0.3-0.4), * weak (0.2-0.3). No star stands for negligible correlation that is too low to be interpreted (≤ 0.2).

The necessity to implement a PM in a contract makes monitoring to the main activity of the RM per design, with risk management only as a spillover. As the contract is not based on the firm's outcome, an increase in the firm's original risk does not motivate an RM to make additional effort. Nevertheless, the relevance of the board's risk aversion is obvious: in case of the board's risk neutrality, the original risk of a firm had virtually no influence on any of the results except the firm's final risk, whereas now it has clear relevance for managerial incentives and the firm's expected utility. The assumption of the risk aversion of the board constitutes the link between the firm's risk and managerial compensation risk when contracts are based on

PMs other than firm's outcome. Thus, the firm's original risk remains relevant to the results, even if contracting on the firm's outcome is not possible, thus allowing an analysis of risk management and not pure monitoring.

Moreover, the board's risk aversion unambiguously constitutes its inner motivation to provide for risk management systems. Per design, the increase of $r_P$ is strongly negatively correlated with the firm's expected utility, as it increases the board's risk premium. I observe in this context, a board-related risk aversion effect, as a more risk-averse board tries to lower the firm's risk through imposition of higher managerial incentives, represented by a weak positive correlation between these incentives and the board's risk aversion. Nonetheless, the effect influences the final precision of the PM rather than the firm's final risk, as the contracts are only based on a proxy. Regarding managerial risk aversion, the existence of the extended risk aversion effect, similar to the risk-neutral case, may be presumed. More risk-averse BUM increases the incentives of the RM; overall, this leads to more risk-management effort and less risk. Furthermore, the risk aversion effect with regard to the RM's risk aversion can also be alleged. Unfortunately, the correlations are weak to negligible, precluding an unambiguous interpretation. This could, however, be due to some hidden effects and not necessarily to the absence of these effects. In case of the board's risk neutrality, I observed the positive influences of (extended) risk aversion effects only for a sufficiently low cost of the risk-management effort. When a simulation is used, the effect is summarized over all the costs of effort and, as a consequence, might be only weakly visible.

Furthermore, I observe that the risk-averse board strives to maintain the same level of risk at the cost of lower expected utility in equilibrium. As the cost of the risk-management effort increases, the incentives increase as well, to sustain a similar level of risk-management effort. The board can only indirectly influence the RM's decision via an increase in the incentives of the BUM. Overall, there is almost no effect of the increase in the cost of the risk-management effort, on the RM's effort and further on the firm's and PM's final risk. This was not given for the risk-neutral case, where the inner motivation of the board to decrease risk is absent. Moreover, one of the typical effects observed in agency is absent: the negative influence of an increase in BUM's risk aversion on her/his incentives and effort, and on the firm's utility. Instead of decreasing these outputs, the increase in the risk aversion of the BUM leads to an increase in risk-management effort, resulting in risk reduction that ostensibly compensates for her/his increased risk aversion so that overall, no effect is visible.

The focus of the managers lies on their compensation risk, which, in the case of contracts based on PMs, is different from the firm's risk. The impact of contracting on a PM that is different from the firm's outcome is clearly visible. The RM is interested only in optimizing her/his own compensation risk and monitoring the BUM's performance, without regard for the firm's risk. In this context, risk management emerges as a spillover of the RM's monitoring activity, not an aim in itself. The board's possibilities to influence the RM's behavior are limited by the available PMs: implementing a less precise PM forces the RM to undertake monitoring activity, spilling over in the form of risk management. A higher effort to decrease her/his compensation risk spills over to strongly decrease the final risk of the firm. Thus, the problem of the choice of a suitable PM regarding conflicting effects on the managers arises. Implementing imprecise PMs leads to lower firm's risk, but also to lower utility, as it is known that imprecise PMs make BUM motivation costlier. Thus, if managerial contracts must be based on the same metric, rather precise PMs should be used; even though they lead to an equilibrium with higher firm's risk, they also allow higher utility. Due to this contradiction, better incentivization of the managers would probably be possible, if the contracts were based on different metrics. Moreover, for RMs, it does not hold true that more precise PMs are better-suited in incentive contracts.

### 4.4.3 Research implications and managerial implications of the study

Insights for research on risk management are two-fold. First, the assumption of risk aversion in risk management research is crucial for the discussion on performance measurement. Moreover, the risk aversion of the principal constitutes the link between the risk of the firm and that of a contracting metric, which is necessary for analysis. Otherwise, the additional complexity does not deliver any further insights, as managerial (extended) risk aversion effects are observed in the case of risk-neutral principals as well. Thus, it appears optimal to conduct risk management research with the assumptions of a contractible firm's outcome and a risk-neutral principal, as this reduces the complexity of the results without returning to a monitoring framework. Even though the principal's inner motivation to provide risk management systems is absent in such a case, there are other reasons to do so, that is, legal regulations and recommendations. In settings where only the risk neutrality of the principal and non-contractibility of the firm's outcome are justifiable, the discussion regarding risk management is limited, as such models are per design ones of monitoring, and the connection to the firm's risk is only accidental. Second, I present a simulation as an alternative method of accounting for the interdependencies between the input and output parameters for models in which the comparative statics are unattainable owing to the high complexity of the results. This opens the possibility of gaining insights into problems that are too complex for analytical research.

The managerial implications of this study extend in two main directions: the choice of suitable managers and the provision of optimal contracts for these managers. As far as the recruitment processes of firms are concerned, the results emphasize the relevance of managerial risk and effort aversion to the firm’s profit and risk. The assessment of potential employees with regard to their risk aversion is already a known practice in recruitment and assessment centers. Firm-managers matching can be further expanded to assess managerial effort aversion. Even though screening the candidates for their aversion to risk and effort does not allow for absolute statements about these parameters, it allows them to be categorized as more or less averse than others. This further enables an optimal employee choice with regard to the risk the firm faces, the organizational structures it maintains, and the managerial contracts it offers.

With regard to the design of contracts for managers, especially those managing risk, two aspects must be accounted for: the form of a contract itself and the performance measure that is used within it. As far as contract form is concerned, only linear contracts have been discussed due to their prevalence in contracting practice, as well as in managerial research. Non-monotone contracts could be an alternative for RMs, although the legal issues of such contracts would need to be broadly addressed. Furthermore, the study clearly shows that contracting with BUMs and RMs on the same performance measure leads to inefficiencies. As RMs’ activities concentrate on managing the variance of the results, and not their expected value, the concept of contracting on results’ variance (Meth 1996) must at least be addressed in practice. Both non-monotone contracts and contracts based on the deviation from expected results have been analyzed in managerial research, mostly in the context of inducing truthful reporting and not incentivizing effort. The contract design would need to be changed, should the aim lie in inducing optimal acceptable deviation from the expected result (understood as optimal firm’s risk or optimal mix of firm’s risk and profit), rather than in obtaining no deviation from the expected value at all, as was the case so far. In particular, the use of options in managerial contracts requires closer attention with regard to its effects on incentives and effort. Empirical research indicates a connection between such contracts and risk-taking behavior (e.g., Hayes et al. 2012), and managerial research has addressed the use of options in contracts for managers in general (e.g., Aseff and Santos 2005). However, the incentivization of RMs should be provided separate attention, as the effects within this special group may diverge.

## 4.5 Conclusions

### 4.5.1 Resumé of the results

Measuring the performance of their managers has always been of high importance for firms. The necessity to incentivize the BUMs and RMs implies that design choices regarding performance measurement and risk management intertwine. Agency theory establishes a tool for analyzing the compensation of risk-averse managers; however, it has to date mostly neglected the analysis of incentives for RMs. Moreover, the risk aversion of the owner of the firm as a driving force of risk management has not been examined so far.

This study aims to fill the gap with respect to decentralized risk management systems. I show that the board's risk aversion motivates it to organize and incentivize such systems. In the absence of moral hazard, risk management is conducted with respect to the firm's risk and existing risk-sharing opportunities. Even with observability of effort, the precision of the PM is significant, as managers with imprecise measures are less ready to accept risk shares, creating the necessity for risk management implementation.

As the analytical results of the second-best problem are quite complex—making the comparative statics difficult to derive and interpret—they are used as a framework for a simulation-based analysis. Simulation is not as robust as mathematical analysis but is nonetheless increasingly accepted as a valuable research method. Using a proxy in the form of a PM with properties other than the firm's outcome, shifts risk management toward monitoring. Nonetheless, due to the board's risk aversion, the firm's original risk remains relevant for the results, as opposed to the case of a risk-neutral board.

From these results, the necessity for re-examination of performance measurement for RMs emerges. The known effects from prior literature, with more precise PMs making managerial incentives less costly, do not hold for RMs. RMs are prompted by less precise PMs to exert more monitoring effort, lowering managerial compensation risk and per spillover the risk for the firm. Nonetheless, incentivization of the BUM's activity always takes precedence over incentivization of the RM. Thus, more precise measures will still be preferred in contracts. Although these equilibria report higher firm's risk, they attain higher firm's utility, as compared to a less precise metric. If the firm's outcome cannot be contracted on, discussions must be held on whether different PMs or contract types must be used for RMs compared to other managers.

The knowledge applicable to the BUMs cannot be transferred to the RMs and the empirically observed contracts for RMs based on the same profit-based measures as other managers must be critically reviewed.

I also deliver two insights relevant for future managerial research. First, risk aversion of the board constitutes inner motivation for introducing risk management, but otherwise the results observed are vastly similar to the case of the risk-neutral board. The correlation between the firm's risk and the risk of the PM, and the assumption of a risk-averse principal—in this case of a risk-averse board—are necessary for risk management research, if the firm's outcome is not available for contracting. Otherwise, assuming the risk aversion of the principal enhances the complexity of the results, without delivering additional insights. Second, I present the possibility to employ simulation to obtain Spearman's rank correlation coefficients as an approximation of the comparative statics for the most complex analytical results, which are otherwise difficult to analyze. Effects observed in this manner are similar to the analytical results in the case of risk neutrality, even if their interpretation is more contestable than mathematical proof.

### 4.5.2 Limitations of the study and avenues for future research

This study has certain limitations resulting from model assumptions and the research method used. As far as model assumptions are concerned, the linearity of contracts, though widely accepted in managerial research, may still exclude some optimal contracts from the analysis. Revising to the standard model of agency theory would, however, hinder the manageability of already highly complex computations. The wide usage of LEN models within agency research allows for certain leniency with this concrete limitation. Furthermore, I only allowed for one PM in contracts for both managers; additional observable signals, possibly correlated with one another, could also be implemented, but would greatly enhance the complexity of the results. Finally, the analysis is restricted to the results that fall within certain, sufficiently low ranges of cost of risk-management effort. Nonetheless, this limitation may reflect the real-world preference for the employment of workers with low effort aversion.

Separate limitations result from the use of simulations. The correlations between the parameters are at times too weak to be unambiguously interpreted; the definition of correlation strength is rather subjective. Furthermore, one must assume that some effects remain hidden, as the simulation clouds aspects such as the differentiated influence of a parameter. Finally, it could be of interest to implement wider intervals for input parameters, especially with regard to the original variance, and to run a higher number of simulation trials.

Overall, even though ambiguity of some results is retained, insight into certain interdependencies within the model is gained, which was otherwise not available because of the high complexity of the results. Future research in the area of risk management could discuss employing other contracts for the RMs and relaxing the LEN assumptions. Alternatively, it could return to the assumption of a risk-neutral owner of the firm and assess more complex organizational structures with multiple managers in this context.

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# 5 Conclusions

## 5.1 Summary and implications

Virtually all firms organize risk management due to legal reasons, implementation of corporate governance, or acceptance of its profitability for firms (OECD 2014; UNECE 2012). RMs can usually be perceived as being similar in their characteristics to other managers in firms, such as CEOs, CFOs, and BUMs, but their activities are fundamentally different. They focus on risk reduction or, more broadly, optimal management of the risks the firms face, and not so much on profit. The organization of risk management, the incentivization of the RMs employed, and the assessment of their performance is essential for firms and policymakers. Agency theory, which deals with contractual relationships in firms and firm organization (Jensen and Meckling 1976), may provide guidance in this context. At its core, risk management deals with reducing variance in a firm's results, a concept similar to the reduction of the variance of PMs in the monitoring framework. Even though risk management seems to be a special case of monitoring, agency models rarely cover it. Hence, a gap in the literature is present, which this thesis aimed to cover partially. Three research questions focus on (1) organization of risk management within firms, (2) optimal incentives for RMs with regard to their characteristics and environmental influences and (3) measuring the RMs' performance.

The first study, *Third-party monitoring and risk management: literature review*, proposes the requirements for modeling risk management within an agency and analyzes the existing monitoring literature in this respect. The main result is that risk management should be perceived as a new research field from the agency theory perspective, as its specific problems are not sufficiently covered in the existing literature. Two distinct exceptions emerge in Meth (1996) and Dürr et al. (2020). For Meth (1996), the reinterpretation is direct, as the variance-reducing, risk- and effort-averse manager is compensated based on the firm's outcome and their effort, thus directly decreasing the risk of the firm and her or his compensation risk. In Dürr et al. (2020), the manager's activity decreases only the variance of the uncertain productivity, which should be seen as part of the firm's overall risk; thus, the reinterpretation is limited.

From these two studies, three important insights for risk management emerge, addressing some issues from the **first and second research questions**. First, the firm's risk is relevant to contracts within firms and can restrict the optimal firm or team size. Second, a delegation of multiple tasks to an RM leads to underinvestment in some of them, implying the relevance of specialization. Third, risk aversion of agents employed as RM is relevant for their incentive scheme, as it determines their readiness for risk-taking or risk reduction, with RMs at times implementing additional effort only due to their risk preference. Overall, many questions remain open, including but not limited to the organization of risk management within a firm's hierarchical structure and the design of incentive schemes for RMs, especially the problem of correct performance measurement, possibly aligning risk of the firm with managerial compensation risk in the absence of a contractible firm's outcome.

The second study, *Organizational design of risk management*, compares the firm's profit and risk for two different hierarchical designs of risk management: centralization, with RM employed directly by the board, and decentralization, with RM employed by the BUM. Centralization implies a board-level committee, whereas decentralization stands for an internal RMS or a CRO implemented at the level of a single BU, as a general representation of an enterprise-wide RMS. The three effects drive the results. First, in decentralization, an increase in RM's risk aversion may lead to more risk-management effort if the cost of this effort is not too high, an effect absent in centralization. Second, an increase in BUM's risk aversion may prompt the party employing the RM to incentivize more risk-management effort, once more, if its cost is not too high. Both these effects aim to diminish the respective managerial compensation risk, directly connected to the firm's risk. Finally, the organizational structure determines the tradeoff between productive and risk-management incentives in the form of marginal risk-management incentives necessary for each additional unit of productive incentives. This tradeoff is always more profitable in decentralization, allowing for higher productive incentives and higher profits. The risk is not a direct object of optimization here; in equilibrium, an optimal mix of profit and risk emerges. Nonetheless, centralization may lead to a lower risk for the firm, as long as the cost of risk-management effort is sufficiently low.

From these observations, two insights into the organization of risk management in firms emerge. First, organizing risk management across hierarchical tiers seems more profitable for the firm than relying only on a board committee. This result partially covers issues from the **first research question** of this thesis. Second, within given organizational structures, firms need to account for the risk aversion of the individuals they employ. Screening for risk and effort aversion may emerge as a pertinent element of recruitment processes. This directly addresses the **second research question**, regarding the individual characteristics of employees in risk-managing roles. Naturally, the insights are subject to limitations resulting from the model assumptions; even so, the findings are in accordance with organizational literature that also proposes the enterprise-wide implementation of risk management. The institutional recommendations opt for aligning the discussed benefits and implementing different structures of risk management parallelly. Such a model, however, would demand separate consideration.

The third study, *Performance measurement in firms with decentralized risk-management and risk-averse board*, aims to partially cover the performance measurement without a contractible firm's outcome. Given the decentralized structure of risk management, a different PM is proposed for managerial contracts, with risk-management effort affecting variances of PM and firm's outcome to the same extent. Moreover, the PM and firm's outcome are correlated, and the owner is modeled as risk-averse to account for her or his interest in risk reduction. Through this model design, the study depicts the activity of an RM as monitoring in its aim, but with risk management per spillover, with the risk of a firm relevant to all main results. The assumption of a principal's risk aversion is essential for interpretation as risk management, as, in the case of risk neutrality, the model reverses to one of pure monitoring. Owing to the high complexity of the analytical results, a simulation was carried out using Oracle Crystal Ball® to interpret the relationship between the input and output parameters.

From the analysis, the dual effect of PM's precision is visible: a more precise measure incentivizes more effort by the BUM, leading to a higher firm's utility, but it also restricts the effort that an RM deems optimal, thus incurring higher firm's risk. Even though it is in line with the common truth of association between higher risk and higher profit, the question emerges whether incentivizing RMs with different PMs than other managers, possibly ones that are not based on profit but still connect to risk, could allow for attaining higher utility while also—if desired or required—decreasing the risk the firm faces. Potential inefficiencies of contracting with RMs, as with any other type of manager, indicate that diverging or unique metrics or even contract forms must be explored. These results address the **third and final research question**, although a broad array of problems still needs further analysis.

From the perspective of the existing research gap in organization and incentivization of risk management, the studies deliver consistent results and potential recommendations for practice. First, as far as hierarchical organization is concerned, decentralization in the form of RMs implemented in single BUs is mildly supported as a more profitable structure. This is especially true for firms that can contract on a firm's outcome and are well-diversified to assume their risk neutrality. The recommendation is particularly relevant for firms obliged to implement risk management but not directly acknowledging its merits. Moreover, risk in itself is a factor restraining the size of a firm, additionally underlining the relevance of risk management in this aspect. Second, the risk itself and aversion to it induce additional risk-management effort, either directly through RM's endeavor to diminish compensation risk or through additional incentives from the party employing an RM, aiming for the same goal. The prevalence of these risk aversion effects remains connected to managerial effort aversion. Such observations result in the postulate of screening job candidates for aversion to effort and risk. On a more general level, they also emphasize the relevance of accounting for interdependencies between the personal traits of single employees. Third, examination of risk management as a component of incentive contracts promotes the idea of task specialization, as delegating both tasks to one manager leads to underinvestment in one of them (Meth 1996). A similar problem is observed when the productive and risk-managing tasks are separated between the two managers, but the contracts are based on the same PM. The assessment of actors managing risk in firms needs reorientation and also a reversal from rigid patterns such as incentivizing all top managers similarly. New contract forms and different PMs for risk management should be considered and tested analytically or empirically.

## 5.2 Limitations and outlook

The studies presented in this thesis, and thus the thesis itself, are subject to limitations, which originate mostly from modeling assumptions. First, the LEN assumptions restrict contract forms that can be implemented within the analysis. Due to tractability, the assumption of linear contracts is widely accepted in the agency theoretical research; it is also the typical form found in managerial incentive schemes in practice. Still, it excludes other, potentially optimal contract forms, and in the context of a variance-reducing activity of an RM, this assumption is the most problematic one. Other contract forms could be better suited for incentivizing such effort, but they would vanquish the accessibility and simplicity of results offered by the LEN models and could, in practice, be met with acceptance issues. In addition, the models presented here are subject to all further critique points, which arise as soon as LEN assumptions are used (Schäfer 2013).

The second limitation results from the representation of risk management within the models; the challenge lies in modeling the actual risk management without switching to the monitoring framework. To do this accurately, the incentive scheme must be specified in a manner that has an RM directly benefitting from engagement in risk management. The model in Chapter 3 accounts for this through an assumption of a contractible firm's outcome; the RM wants to decrease its own compensation risk and thus implements variance-reducing effort, which is, as per definition, the same as risk management. Meanwhile, the model in Chapter 4 bases the contract on a chosen PM so that reducing its variance also reduces the firm's risk. Although the effort of an RM still has risk-managing quality, the intention of an RM is a decrease in the compensation risk and not in the risk of a firm. In this second case, if the firm's risk was not affected by RM's action, they would still opt for the same effort. Hence, only when a firm's outcome is contractible is it possible to model risk management directly and not just as a spillover of an activity intended to be monitoring. This limitation necessitates research on other contract forms and PMs that align the effort of an RM and decrease the firm's risk.

Moreover, the simulation as a research method used in Chapter 4 has certain limitations. The one most often discussed is the simulation as a "black box," in which the mechanics of the model are not clear, and only a series of inputs and outputs are presented. This limitation is mostly avoided in the thesis because the mechanics of the model are provided analytically, and a simulation is only implemented as an approximation of comparative statics. However, from this approach stems a different limitation: at times, the strength of the obtained correlation coefficients is insufficient. This is a serious problem that may cloud the true relation between input and output. In Chapter 3, some effects were observed or absent, depending on the development of a parameter. When the simulation is used, only the overall effect is visible. Thus, a non-existent correlation can be attributed either to the missing relationship between the variables or to the mixed influence of the input parameter on the output variable; an accurate interpretation is not available.

Finally, not all problems depicted in Chapter 1 could have been addressed, thus limiting the thesis' scope. Regarding the organization of risk management, two primary aspects remain open: the interdependencies between risk management structure and the firm's size and parallel employment of centralized and decentralized organizational structures. Regarding the characteristics of individuals within firms, the focus has been placed on risk and effort aversion, in effect, disregarding problems such as altruism or envy in the context of risk management incentivization. Finally, questions regarding the number of PMs, value of additional PMs, and interdependencies between the managers or BUs in the case of different contractual metrics for different tasks have not been considered.

Hence, further studies could examine the simultaneous use of different organizational risk management structures to depict institutional recommendations more accurately. Of particular interest is the influence of risk management on other types of efforts, such as coordination, supporting, monitoring, or contracting, provided by other managers in a more complex hierarchy. Utility maximization, given an acceptable risk level, could be considered. Furthermore, investigating different metrics as a base for RMs' contracts and their influence on managerial behavior is pertinent. On the one hand, a more accurate depiction of contracts observed in practice could be worth striving for to better understand empirically observed effects. On the other hand, the proposition of new contractual metrics could prove relevant for future contractual practices. Finally, the simulation presented here could be an opportunity for managerial research to address more complex problems. As such, this thesis can be seen as a starting point for future agency theoretical research on risk management.

# Appendix

## A1. Derivation of Lemma 1 (centralization)

The certainty equivalent of the BUM from (5) is defined as follows:

$$CE_B^c = a \cdot \alpha \cdot e^c + b - \frac{1}{2} \cdot \left(e^c\right)^2 - \frac{1}{2} \cdot r_B \cdot a^2 \cdot \frac{\sigma^2}{1+m^c} \quad .$$

Thus, from the incentive constraint of the BUM we derive:

$$\frac{\partial CE_B^c}{\partial e^c} = a \cdot \alpha - e^c \overset{!}{=} 0 \Leftrightarrow e^c = a \cdot \alpha \quad .$$

For an RM, we assume for simplification, that her/his true risk aversion is actually defined by $r_R{}' = 2 \cdot r_R$. This results in the shortened certainty equivalent in (6), leading to:

$$CE_R^c = a_R \cdot \alpha \cdot e^c + b_R - k \cdot m^c - r_R \cdot a_R^2 \cdot \frac{\sigma^2}{1+m^c} \quad .$$

Thus, from the incentive constraint of the RM we derive:

$$\frac{\partial CE_R^c}{\partial m^c} = -k + r_R \cdot a_R^2 \cdot \frac{\sigma^2}{\left(1+m^c\right)^2} \overset{!}{=} 0 \Leftrightarrow m^c = a_R \cdot \sqrt{\frac{r_R \cdot \sigma^2}{k}} - 1 \, .$$

Thus, the problem of the owner under individual rationality constraints of BUM and RM:

$$\Pi^c = \alpha \cdot e^c - \frac{1}{2} \cdot \left(e^c\right)^2 - k \cdot m^c - \left( r_R \cdot a_R^2 + \frac{1}{2} \cdot r_B \cdot a^2 \right) \cdot \frac{\sigma^2}{1+m^c} \quad .$$

And under the incentive constraints of BUM and RM:

$$\Pi^c = \alpha^2 \cdot a - \frac{1}{2} \cdot \alpha^2 \cdot a^2 - a_R \cdot \sqrt{k \cdot r_R \cdot \sigma^2} + k - \left( r_R \cdot a_R + \frac{1}{2} \cdot r_B \cdot \frac{a^2}{a_R} \right) \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \quad .$$

This leads to optimal contracts for the owner:

$$\frac{\partial \Pi^c}{\partial a} = \alpha^2 - \alpha^2 \cdot a - r_B \cdot \frac{a}{a_R} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \overset{!}{=} 0 \, ,$$

$$\frac{\partial \Pi^c}{\partial a_R} = -\sqrt{k \cdot r_R \cdot \sigma^2} - \left( r_R - \frac{1}{2} \cdot r_B \cdot \frac{a^2}{a_R^2} \right) \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \overset{!}{=} 0 \Leftrightarrow \frac{a}{a_R} = 2 \cdot \sqrt{\frac{r_R}{r_B}} \, .$$

Thus, optimal results:

$$a^c = 1 - \frac{2 \cdot \sqrt{r_B \cdot k \cdot \sigma^2}}{\alpha^2} \, ,$$

$$a_R^c = \frac{1}{2} \cdot a^c \cdot \sqrt{\frac{r_B}{r_R}} = \frac{1}{2} \cdot \left( 1 - \frac{2 \cdot \sqrt{r_B \cdot k \cdot \sigma^2}}{\alpha^2} \right) \cdot \sqrt{\frac{r_B}{r_R}} \, ,$$

$$e^c = \alpha \cdot \left(1 - \frac{2 \cdot \sqrt{r_B \cdot k \cdot \sigma^2}}{\alpha^2}\right),$$

$$m^c = a_R^c \cdot \sqrt{\frac{r_R \cdot \sigma^2}{k}} - 1 = \frac{1}{2} \cdot \sqrt{\frac{r_B \cdot \sigma^2}{k}} - \frac{r_B \cdot \sigma^2}{\alpha^2} - 1,$$

$$\sigma^2_{eff,c} = \frac{\sigma^2}{1 + m^c} = \left(\frac{1}{2} \cdot \sqrt{\frac{r_B}{k \cdot \sigma^2}} - \frac{r_B}{\alpha^2}\right)^{-1},$$

$$\Pi^c = \frac{1}{2} \cdot \alpha^2 \cdot \left(a^c\right)^2 + k = \frac{1}{2} \cdot \alpha^2 \cdot \left(1 - \frac{2 \cdot \sqrt{r_B \cdot k \cdot \sigma^2}}{\alpha^2}\right)^2 + k.$$

## A2. Relevant bounds for Lemma 1 (centralization)

The efforts and incentives of the managers must be non-negative. From this requirement, we can derive two necessary assumptions regarding the cost of risk-management effort.

From (8b): $a_B^c \geq 0 \Leftrightarrow 1 - \frac{2 \cdot \sqrt{r_B \cdot k \cdot \sigma^2}}{\alpha^2} \geq 0 \Leftrightarrow \sqrt{k} \leq \frac{\alpha^2}{2 \cdot \sqrt{r_B \cdot \sigma^2}}$.

From (8c): $m^c \geq 0 \Leftrightarrow \sqrt{k} \leq \frac{\alpha^2 \cdot \sqrt{r_B \cdot \sigma^2}}{2 \cdot \left(\alpha^2 + r_B \cdot \sigma^2\right)}$.

To find the binding restriction, we compare the bounds with one another:

$$k\left(m^c\right) < k\left(a_B^c\right) \Leftrightarrow \frac{\alpha^2 \cdot \sqrt{r_B \cdot \sigma^2}}{2 \cdot \left(\alpha^2 + r_B \cdot \sigma^2\right)} < \frac{\alpha^2}{2 \cdot \sqrt{r_B \cdot \sigma^2}} \Leftrightarrow \frac{r_B \cdot \sigma^2}{\left(\alpha^2 + r_B \cdot \sigma^2\right)} < 1.$$

Binding is the most restrictive (the smallest) upper bound, which is

$$\sqrt{k} \leq \frac{\alpha^2 \cdot \sqrt{r_B \cdot \sigma^2}}{2 \cdot \left(\alpha^2 + r_B \cdot \sigma^2\right)} \equiv \omega_0^c.$$

## A3. (Extended) risk aversion and incentive effects in centralization

We derive the part of equation (24) regarding centralization as follows:

$$\frac{\partial m^c}{\partial r_R} = \underbrace{\frac{\partial a_R^c}{\partial r_R} \cdot \sqrt{\frac{\sigma^2 \cdot r_R}{k}}}_{\substack{<0 \\ \text{incentive effect}}} + \underbrace{a_R^c \cdot \sqrt{\frac{\sigma^2}{4 \cdot k \cdot r_R}}}_{\substack{>0 \\ \text{risk aversion effect}}} = \underbrace{-a_B^c \cdot \frac{1}{4 \cdot r_R} \cdot \sqrt{\frac{\sigma^2 \cdot r_B}{k}}}_{\substack{<0 \\ \text{incentive effect}}} + \underbrace{a_B^c \cdot \frac{1}{4 \cdot r_R} \cdot \sqrt{\frac{\sigma^2 \cdot r_B}{k}}}_{\substack{>0 \\ \text{risk aversion effect}}} = 0 .$$

For equation (25), we need the following derivation:

$$\frac{\partial a_R^c}{\partial r_B} = \underbrace{\frac{\partial a_B^c}{\partial r_B} \cdot \frac{1}{2} \cdot \sqrt{\frac{r_B}{r_R}}}_{\substack{<0 \\ \text{extended incentive effect}}} + \underbrace{\frac{a_B^c}{4 \cdot \sqrt{r_R \cdot r_B}}}_{\substack{>0 \\ \text{extended risk aversion effect}}} = \frac{1}{4 \cdot \sqrt{r_R \cdot r_B}} - \frac{1}{\alpha^2} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} .$$

The derivative is positive when the cost of risk-management effort is sufficiently low:

$$\frac{\partial a_R^c}{\partial r_B} > 0 \Leftrightarrow \sqrt{k} < \frac{\alpha^2}{4 \cdot \sqrt{r_B \cdot \sigma^2}} \equiv \omega_1^c .$$

We need to compare the new restriction with the original bound:

$$\omega_1^c < \omega_0^c \Leftrightarrow \frac{\alpha^2}{4 \cdot \sqrt{r_B \cdot \sigma^2}} < \frac{\alpha^2 \cdot \sqrt{r_B \cdot \sigma^2}}{2 \cdot \left(\alpha^2 + r_B \cdot \sigma^2\right)} \Leftrightarrow \frac{1}{2} < \frac{r_B \cdot \sigma^2}{\left(\alpha^2 + r_B \cdot \sigma^2\right)} ,$$

which is not conclusive; thus,

$$\frac{\partial a_R^c}{\partial r_B} > 0 \quad \forall k : \sqrt{k} \in \left[0, \ \min\left\{\omega_1^c ; \omega_0^c\right\}\right)$$

$$\frac{\partial a_R^c}{\partial r_B} < 0 \quad \forall k : \sqrt{k} \in \left(\min\left\{\omega_1^c ; \omega_0^c\right\}, \ \omega_0^c\right].$$

The effect transitions to risk-management effort:

$$\frac{\partial m^c}{\partial r_B} = \frac{\partial a_R^c}{\partial r_B} \cdot \sqrt{\frac{r_R \cdot \sigma^2}{k}} .$$

Thus,

$$\frac{\partial m^c}{\partial r_B} > 0 \quad \forall k : \sqrt{k} \in \left[0, \ \min\left\{\omega_1^c ; \omega_0^c\right\}\right)$$

$$\frac{\partial m^c}{\partial r_B} < 0 \quad \forall k : \sqrt{k} \in \left(\min\left\{\omega_1^c ; \omega_0^c\right\}, \ \omega_0^c\right].$$

## A4. Excerpts from other comparative statics in centralization

We observe effects similar to the incentive and risk aversion effects when we derive the results for a firm's original risk before risk management:

$$\frac{\partial m^c}{\partial \sigma^2} = \frac{1}{4} \cdot \sqrt{\frac{r_B}{k \cdot \sigma^2}} - \frac{r_B}{\alpha^2} > 0 \Leftrightarrow \sqrt{k} < \omega_1^c$$

$$\frac{\partial m^c}{\partial \sigma^2} > 0 \quad \forall k: \ \sqrt{k} \in \left[0, \ \min\left\{\omega_1^c; \omega_0^c\right\}\right)$$

$$\frac{\partial m^c}{\partial \sigma^2} < 0 \quad \forall k: \ \sqrt{k} \in \left(\min\left\{\omega_1^c; \omega_0^c\right\}, \ \omega_0^c\right].$$

The effects on risk-management effort transition further to the firm's final risk:

$$\frac{\partial \sigma^2_{eff,c}}{\partial \sigma^2} = \left(\frac{1}{2} \cdot \sqrt{\frac{r_B}{k \cdot \sigma^2}} - \frac{r_B}{\alpha^2}\right)^{-2} \cdot \frac{1}{4} \cdot \sqrt{\frac{r_B}{k \cdot \left(\sigma^2\right)^3}} > 0,$$

$$\frac{\partial \sigma^2_{eff,c}}{\partial r_B} = -\left(\frac{1}{2} \cdot \sqrt{\frac{r_B}{k \cdot \sigma^2}} - \frac{r_B}{\alpha^2}\right)^{-2} \cdot \left(\frac{1}{4} \cdot \sqrt{\frac{1}{k \cdot \sigma^2 \cdot r_B}} - \frac{1}{\alpha^2}\right),$$

$$\frac{\partial \sigma^2_{eff,c}}{\partial r_B} < 0 \Leftrightarrow -\left(\frac{1}{2} \cdot \sqrt{\frac{r_B}{k \cdot \sigma^2}} - \frac{r_B}{\alpha^2}\right)^{-2} \cdot \left(\frac{1}{4} \cdot \sqrt{\frac{1}{k \cdot \sigma^2 \cdot r_B}} - \frac{1}{\alpha^2}\right) < 0 \Leftrightarrow \sqrt{k} < \omega_1^c,$$

$$\frac{\partial \sigma^2_{eff,c}}{\partial r_B} < 0 \quad \forall k: \ \sqrt{k} \in \left[0, \ \min\left\{\omega_1^c; \omega_0^c\right\}\right)$$

$$\frac{\partial \sigma^2_{eff,c}}{\partial r_B} > 0 \quad \forall k: \ \sqrt{k} \in \left(\min\left\{\omega_1^c; \omega_0^c\right\}, \ \omega_0^c\right].$$

| | $\frac{\partial}{\partial r_B}$ | $\frac{\partial}{\partial r_R}$ | $\frac{\partial}{\partial k}$ | $\frac{\partial}{\partial \alpha}$ | $\frac{\partial}{\partial \sigma^2}$ |
|---|---|---|---|---|---|
| $e$ | $< 0$ | 0 | $< 0$ | $> 0$ | $< 0$ |
| $m$ | $> 0 \quad \forall k:$ $\sqrt{k} \in \left[0, \ \min\left\{\omega_1^c; \omega_0^c\right\}\right)$ $< 0 \quad \forall k:$ $\sqrt{k} \in \left(\min\left\{\omega_1^c; \omega_0^c\right\}, \ \omega_0^c\right]$ | 0 | $< 0$ | $> 0$ | $> 0 \quad \forall k:$ $\sqrt{k} \in \left[0, \ \min\left\{\omega_1^c; \omega_0^c\right\}\right)$ $< 0 \quad \forall k:$ $\sqrt{k} \in \left(\min\left\{\omega_1^c; \omega_0^c\right\}, \ \omega_0^c\right]$ |
| $a_B$ | $< 0$ | 0 | $< 0$ | $> 0$ | $< 0$ |
| $a_R$ | $> 0 \quad \forall k:$ $\sqrt{k} \in \left[0, \ \min\left\{\omega_1^c; \omega_0^c\right\}\right)$ $< 0 \quad \forall k:$ $\sqrt{k} \in \left(\min\left\{\omega_1^c; \omega_0^c\right\}, \ \omega_0^c\right]$ | $< 0$ | $< 0$ | $> 0$ | $< 0$ |
| $\Pi$ | $< 0$ | 0 | $< 0$ | $> 0$ | $< 0$ |
| $\sigma_{eff}^2$ | $< 0 \quad \forall k:$ $\sqrt{k} \in \left[0, \ \min\left\{\omega_1^c; \omega_0^c\right\}\right)$ $> 0 \quad \forall k:$ $\sqrt{k} \in \left(\min\left\{\omega_1^c; \omega_0^c\right\}, \ \omega_0^c\right]$ | 0 | $> 0$ | $< 0$ | $> 0$ |

**Tab. 2** **Comparative statics for optimal results under centralization when the firm's outcome is available as a performance measure.** The first column of the table determines which output parameter is derived and analyzed with respect to the input parameter from the first row of the table. The additional bounds in cases in which the direction of the derivative differs for low and high risk-management effort cost, are defined in the Appendix A4.

### A5. Derivation of Lemma 2 (decentralization)

The certainty equivalent of the RM from (6) is still specified as:

$$CE_R^d = a_R \cdot \alpha \cdot e^d + b_R - k \cdot m^d - r_R \cdot a_R^2 \cdot \frac{\sigma^2}{1+m^d} \ .$$

Thus, from the incentive constraint of the RM:

$$\frac{\partial CE_R^d}{\partial m^d} = -k + r_R \cdot a_R^2 \cdot \frac{\sigma^2}{\left(1+m^d\right)^2} \stackrel{!}{=} 0 \Leftrightarrow m^d = a_R \cdot \sqrt{\frac{r_R \cdot \sigma^2}{k}} - 1 \, .$$

The problem of the BUM under individual rationality constraint of RM:

$$CE_B^d = a \cdot \alpha \cdot e^d + b - k \cdot m^d - \frac{1}{2} \cdot \left(e^d\right)^2 - \left(\frac{1}{2} \cdot r_B \cdot \left(a - a_R\right)^2 + r_R \cdot a_R^2\right) \cdot \frac{\sigma^2}{1+m^d} \ .$$

Under the incentive constraint of RM:

$$CE_B^d = a \cdot \alpha \cdot e^d + b + k - \frac{1}{2} \cdot \left(e^d\right)^2 - \left(\frac{1}{2} \cdot r_B \cdot \frac{a^2}{a_R} - a \cdot r_B + \frac{1}{2} \cdot r_B \cdot a_R + 2 \cdot r_R \cdot a_R\right) \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \, .$$

Thus, optimal effort and contract of the BUM for the RM:

$$\frac{\partial CE_B^d}{\partial e^d} = a \cdot \alpha - e^d \stackrel{!}{=} 0 \Leftrightarrow e^d = a \cdot \alpha \ ,$$

$$\frac{\partial CE_B^d}{\partial a_R} = -\sqrt{k \cdot r_R \cdot \sigma^2} - \left(-\frac{1}{2} \cdot r_B \cdot \frac{a^2}{a_R^2} + \left(\frac{1}{2} \cdot r_B + r_R\right)\right) \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \stackrel{!}{=} 0 \Leftrightarrow a_R = \frac{a}{\sqrt{\frac{4 \cdot r_R + r_B}{r_B}}} \ .$$

Thus, certainty equivalent of the BUM with respect to the optimal contract of the BUM for the RM:

$$CE_B^d = a \cdot \alpha \cdot e^d + b + k - \frac{1}{2} \cdot \left(e^d\right)^2 - a \cdot r_B \cdot \left(\sqrt{\frac{4 \cdot r_R + r_B}{r_B}} - 1\right) \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \ .$$

Owner has the following optimization problem:

$$\begin{aligned} &\max_{a^d} \quad \Pi^d = E\left[\tilde{x} - v\left(\tilde{x}\right)\right] \\ &s.t. \quad (PC_B): CE_B^d(e^{d,*}) \geq 0 \\ &\qquad\ \ (IC_B): e^d \in \arg\max_{e^{d,*} \in E} \left\{CE_B^d(e^{d,*})\right\}. \end{aligned}$$

Thus, the problem of the owner under individual rationality and incentive constraint of BUM:

$$\Pi^d = \alpha^2 \cdot a + k - \frac{1}{2} \cdot \alpha^2 \cdot a^2 - a \cdot r_B \cdot \left(\sqrt{\frac{4 \cdot r_R + r_B}{r_B}} - 1\right) \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \ .$$

Thus, optimal effort and contract of the BUM for the RM:

$$\frac{\partial \Pi^d}{\partial a} = \alpha^2 - r_B \cdot \left( \sqrt{\frac{4 \cdot r_R + r_B}{r_B}} - 1 \right) \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} - \alpha^2 \cdot a \overset{!}{=} 0$$

$$\Leftrightarrow a = 1 - \frac{r_B}{\alpha^2} \cdot \left( \sqrt{\frac{4 \cdot r_R + r_B}{r_B}} - 1 \right) \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}}.$$

This leads to optimal results:

$$a^d = 1 - \left( \sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1 \right) \cdot \frac{r_B}{\alpha^2} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \;,$$

$$a_R^d = a^d \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} = \left( 1 - \left( \sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1 \right) \cdot \frac{r_B}{\alpha^2} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \right) \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} \;,$$

$$e^d = \alpha \cdot a^d = \alpha - \left( \sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1 \right) \cdot \frac{r_B}{\alpha} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \,,$$

$$m^d = a_R^d \cdot \sqrt{\frac{\sigma^2 \cdot r_R}{k}} - 1 = a^d \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} \cdot \sqrt{\frac{\sigma^2 \cdot r_R}{k}} - 1$$

$$= \left( 1 - \left( \sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1 \right) \cdot \frac{r_B}{\alpha^2} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \right) \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} \cdot \sqrt{\frac{\sigma^2 \cdot r_R}{k}} - 1,$$

$$\sigma_{eff,d}^2 = \frac{\sigma^2}{1 + m^d} = \left( \sqrt{\frac{r_B \cdot r_R}{k \cdot (r_B + 4 \cdot r_R) \cdot \sigma^2}} - \left( 1 - \sqrt{\frac{r_B}{(r_B + 4 \cdot r_R)}} \right) \cdot \frac{r_B}{\alpha^2} \right)^{-1},$$

$$\Pi^d = \frac{1}{2} \cdot \alpha^2 \cdot \left(a^d\right)^2 + k = \frac{1}{2} \cdot \alpha^2 \cdot \left( 1 - \left( \sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1 \right) \cdot \frac{r_B}{\alpha^2} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \right)^2 + k \,.$$

## A6. Relevant bounds for Lemma 2 (decentralization)

The efforts and incentives of the managers must be non-negative. From this requirement, we can derive two necessary assumptions regarding the cost of risk-management effort.

From (11b): $a_B^d \geq 0 \Leftrightarrow \sqrt{k} \leq \frac{\alpha^2}{\sqrt{r_B \cdot (r_B + 4 \cdot r_R)} - r_B} \cdot \sqrt{\frac{r_R}{\sigma^2}}$.

From (11c): $m^d \geq 0 \Leftrightarrow \sqrt{k} \leq \frac{\sqrt{r_R \cdot \sigma^2}}{\left(\sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1\right) \cdot \frac{r_B \cdot \sigma^2}{\alpha^2} + \sqrt{\frac{r_B + 4 \cdot r_R}{r_B}}}$.

To find the binding restriction, we must compare the bounds with one another:

$$k\left(m^d\right) < k\left(a_B^d\right)$$

$$\Leftrightarrow \frac{\sqrt{r_R \cdot \sigma^2}}{\left(\sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1\right) \cdot \frac{r_B \cdot \sigma^2}{\alpha^2} + \sqrt{\frac{r_B + 4 \cdot r_R}{r_B}}} < \frac{\alpha^2}{\sqrt{r_B \cdot (r_B + 4 \cdot r_R)} - r_B} \cdot \sqrt{\frac{r_R}{\sigma^2}}$$

$$\Leftrightarrow \alpha^2 \cdot \sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} > 0.$$

Binding is the most restrictive (the smallest) upper bound, which is

$$\sqrt{k} \leq \frac{\sqrt{r_R \cdot \sigma^2}}{\left(\sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1\right) \cdot \frac{r_B \cdot \sigma^2}{\alpha^2} + \sqrt{\frac{r_B + 4 \cdot r_R}{r_B}}} \equiv \omega_0^d .$$

### A7. (Extended) risk aversion and incentive effects in decentralization

For the risk-management incentives, we obtain

$$\frac{\partial a_R^d}{\partial r_R} = \frac{\partial a_B^d}{\partial r_R} \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} - 2 \cdot a_B^d \cdot \sqrt{\frac{r_B}{\left(r_B + 4 \cdot r_R\right)^3}} < 0 \ .$$

For equation (24), we need the following derivation:

$$\frac{\partial m^d}{\partial r_R} = \underbrace{\frac{\partial a_R^d}{\partial r_R} \cdot \sqrt{\frac{\sigma^2 \cdot r_R}{k}}}_{\substack{<0 \\ \text{incentive effect}}} + \underbrace{\frac{a_R^d}{2} \cdot \sqrt{\frac{\sigma^2}{k \cdot r_R}}}_{\substack{>0 \\ \text{risk aversion effect}}}$$

$$= \frac{r_B \cdot \sigma^2}{2 \cdot \alpha^2 \cdot r_R} \cdot \left( \frac{\alpha^2 \cdot r_R}{\sqrt{k \cdot r_R \cdot \sigma^2} \cdot \left(r_B + 4 \cdot r_R\right)} + \frac{r_B}{\left(r_B + 4 \cdot r_R\right)} - 1 \right) \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}}.$$

The derivative is positive when the cost of risk-management effort is sufficiently low:

$$\frac{\partial m^d}{\partial r_R} > 0 \Leftrightarrow \sqrt{k} < \frac{\alpha^2}{4 \cdot \sqrt{r_R \cdot \sigma^2}} \equiv \omega_1^d \ .$$

We need to compare the new restriction with the original bound:

$$\omega_1^d > \omega_0^d$$

$$\Leftrightarrow \frac{\alpha^2}{4 \cdot \sqrt{r_R \cdot \sigma^2}} > \frac{\sqrt{r_R \cdot \sigma^2}}{\left( \sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1 \right) \cdot \frac{r_B \cdot \sigma^2}{\alpha^2} + \sqrt{\frac{r_B + 4 \cdot r_R}{r_B}}} \Leftrightarrow \left(r_B \cdot \sigma^2 + \alpha^2\right) - \sqrt{r_B \cdot \left(r_B + 4 \cdot r_R\right)} \cdot \sigma^2 > 0,$$

which is not conclusive; thus,

$$\frac{\partial m^d}{\partial r_R} > 0 \quad \forall k: \ \sqrt{k} \in \left[0, \ \min\left\{\omega_1^d; \omega_0^d\right\}\right)$$

$$\frac{\partial m^d}{\partial r_R} < 0 \quad \forall k: \ \sqrt{k} \in \left(\min\left\{\omega_1^d; \omega_0^d\right\}, \ \omega_0^d\right].$$

For equation (26) we need the following derivation:

$$\frac{\partial a_R^d}{\partial r_B} = \underbrace{\frac{\partial a^d}{\partial r_B} \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}}}_{\substack{<0 \\ \text{extended incentive effect}}} + \underbrace{a^d \cdot \frac{2 \cdot r_R}{\sqrt{r_B \cdot \left(r_B + 4 \cdot r_R\right)^3}}}_{\substack{>0 \\ \text{extended risk aversion effect}}}$$

$$= \sqrt{\frac{1}{r_B \cdot \left(r_B + 4 \cdot r_R\right)^3}} \cdot 2 \cdot r_R - \frac{1}{\alpha^2} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \cdot \underbrace{\left( 1 - \left( 1 + \frac{2 \cdot r_R}{r_B + 4 \cdot r_R} \right) \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} \right)}_{>0}.$$

Additional computation:

$$1-\left(1+\frac{2\cdot r_R}{r_B+4\cdot r_R}\right)\cdot\sqrt{\frac{r_B}{r_B+4\cdot r_R}}>0\Leftrightarrow 24\cdot r_R^2\cdot r_B+64\cdot r_R^3>0\ ,$$

which is always true. The derivative is positive when the cost of risk-management effort is sufficiently low:

$$\frac{\partial a_R^d}{\partial r_B}>0\Leftrightarrow\sqrt{k}<\sqrt{\frac{r_R}{\sigma^2}}\cdot\frac{r_R\cdot 2\cdot\alpha^2}{\left(\sqrt{r_B\cdot\left(r_B+4\cdot r_R\right)^3}-r_B\cdot\left(r_B+6\cdot r_R\right)\right)}\equiv\omega_2^d\ .$$

We need to compare the new restriction with the original bound:

$$\omega_2^d>\omega_0^d$$

$$\Leftrightarrow\frac{2\cdot\alpha^2\cdot\sqrt{r_R^3}}{\sqrt{r_B\cdot\sigma^2\cdot\left(r_B+4\cdot r_R\right)^3}\cdot\left(1-\left(1+\frac{2\cdot r_R}{r_B+4\cdot r_R}\right)\cdot\sqrt{\frac{r_B}{r_B+4\cdot r_R}}\right)}>\frac{\sqrt{r_R\cdot\sigma^2}}{\left(\sqrt{\frac{r_B+4\cdot r_R}{r_B}}-1\right)\cdot\frac{r_B\cdot\sigma^2}{\alpha^2}+\sqrt{\frac{r_B+4\cdot r_R}{r_B}}}$$

$$\Leftrightarrow 2\cdot\alpha^2\cdot r_R\cdot\left(\left(\sqrt{\frac{r_B+4\cdot r_R}{r_B}}-1\right)\cdot\frac{r_B\cdot\sigma^2}{\alpha^2}+\sqrt{\frac{r_B+4\cdot r_R}{r_B}}\right)$$

$$>\sigma^2\cdot\sqrt{r_B\cdot\left(r_B+4\cdot r_R\right)^3}\cdot\left(1-\left(1+\frac{2\cdot r_R}{r_B+4\cdot r_R}\right)\cdot\sqrt{\frac{r_B}{r_B+4\cdot r_R}}\right),$$

which is not conclusive; thus,

$$\frac{\partial a_R^d}{\partial r_B}>0\quad\forall k:\ \sqrt{k}\in\left[0,\ min\left\{\omega_2^d;\omega_0^d\right\}\right)$$

$$\frac{\partial a_R^d}{\partial r_B}<0\quad\forall k:\ \sqrt{k}\in\left(min\left\{\omega_2^d;\omega_0^d\right\},\ \omega_0^d\right].$$

Then, for risk-management effort,

$$\frac{\partial m^{d,SB}}{\partial r_B}=\frac{\partial a_R^{d,SB}}{\partial r_B}\cdot\sqrt{\frac{\sigma^2\cdot r_R}{k}}\ .$$

Thus,

$$\frac{\partial m^d}{\partial r_B}<0\quad\forall k:\ \sqrt{k}\in\left[0,\ \min\left\{\omega_2^d;\omega_0^d\right\}\right)$$

$$\frac{\partial m^d}{\partial r_B}>0\quad\forall k:\ \sqrt{k}\in\left(\min\left\{\omega_2^d;\omega_0^d\right\},\ \omega_0^d\right].$$

## A8. Excerpts from other comparative statics in decentralization

We observe effects similar to the risk aversion effect when we derive the results for the firm's original risk before risk management:

$$\frac{\partial m^d}{\partial \sigma^2} = \frac{1}{2} \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} \cdot \sqrt{\frac{r_R}{\sigma^2 \cdot k}} - \left( \sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1 \right) \cdot \frac{r_B}{\alpha^2} \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} .$$

The derivative is positive when the cost of risk-management effort is sufficiently low:

$$\frac{\partial m^d}{\partial \sigma^2} > 0 \Leftrightarrow \sqrt{k} < \sqrt{\frac{r_R}{\sigma^2}} \cdot \frac{\alpha^2}{2 \cdot r_B} \cdot \left( \sqrt{\frac{r_B + 4 \cdot r_R}{r_B}} - 1 \right)^{-1} \equiv \omega_3^d .$$

We need to compare the new restrictions with the original bound:

$$\omega_3^d > \omega_0^d \Leftrightarrow \alpha^2 > r_B \cdot \sigma^2 \cdot \left( 1 - \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} \right),$$

which is not conclusive; thus,

$$\frac{\partial m^d}{\partial \sigma^2} > 0 \quad \forall k: \ \sqrt{k} \in \left[ 0, \ \min\left\{ \omega_3^d ; \omega_0^d \right\} \right)$$

$$\frac{\partial m^d}{\partial \sigma^2} < 0 \quad \forall k: \ \sqrt{k} \in \left( \min\left\{ \omega_3^d ; \omega_0^d \right\}, \ \omega_0^d \right].$$

The effects on risk-management effort transition further to the firm's final risk:

$$\frac{\partial \sigma^2_{eff,d}}{\partial r_B} = -\left( \sqrt{\frac{r_B \cdot r_R}{k \cdot \left( r_B + 4 \cdot r_R \right) \cdot \sigma^2}} - \left( 1 - \sqrt{\frac{r_B}{\left( r_B + 4 \cdot r_R \right)}} \right) \cdot \frac{r_B}{\alpha^2} \right)^{-2}$$
$$\cdot \left( 2 \cdot r_R \cdot \sqrt{\frac{r_R}{k \cdot \sigma^2 \cdot r_B \cdot \left( r_B + 4 \cdot r_R \right)^3}} - \frac{1}{\alpha^2} + \sqrt{\frac{r_B}{\left( r_B + 4 \cdot r_R \right)^3}} \cdot \frac{r_B + 6 \cdot r_R}{\alpha^2} \right),$$

$$\frac{\partial \sigma^2_{eff,d}}{\partial r_B} < 0 \Leftrightarrow \sqrt{k} < \frac{2 \cdot r_R \cdot \alpha^2 \cdot \sqrt{\dfrac{r_R}{\sigma^2 \cdot r_B \cdot \left( r_B + 4 \cdot r_R \right)^3}}}{1 - \sqrt{\dfrac{r_B}{\left( r_B + 4 \cdot r_R \right)^3}} \cdot \left( r_B + 6 \cdot r_R \right)} \Leftrightarrow \sqrt{k} < \omega_2^d .$$

Thus,

$$\frac{\partial \sigma^2_{eff,d}}{\partial r_B} < 0 \quad \forall k: \ \sqrt{k} \in \left[ 0, \ \min\left\{ \omega_2^d ; \omega_0^d \right\} \right)$$

$$\frac{\partial \sigma^2_{eff,d}}{\partial r_B} > 0 \quad \forall k: \ \sqrt{k} \in \left( \min\left\{ \omega_2^d ; \omega_0^d \right\}, \ \omega_0^d \right],$$

$$\frac{\partial\sigma^2_{eff,d}}{\partial r_R} = -\left(\sqrt{\frac{r_B\cdot r_R}{k\cdot(r_B+4\cdot r_R)\cdot\sigma^2}} - \left(1-\sqrt{\frac{r_B}{(r_B+4\cdot r_R)}}\right)\cdot\frac{r_B}{\alpha^2}\right)^{-2}$$

$$\cdot\left(\frac{1}{2}\cdot\sqrt{\frac{r_B}{k\cdot\sigma^2}}\cdot\sqrt{\frac{r_B+4\cdot r_R}{r_R}} - 2\cdot\sqrt{\frac{r_B}{r_B+4\cdot r_R}}\cdot\frac{1}{\alpha^2}\right)\cdot\frac{r_B}{(r_B+4\cdot r_R)^2}.$$

The derivative is positive when the cost of risk-management effort is sufficiently low:

$$\frac{\partial\sigma^2_{eff,d}}{\partial r_R} < 0 \Leftrightarrow \sqrt{k} < \frac{\alpha^2\cdot(r_B+4\cdot r_R)}{4\cdot\sqrt{\sigma^2\cdot r_R}} \equiv \omega_4^d \ .$$

We need to compare the new restriction with the original bound:

$$\omega_4^d > \omega_0^d$$

$$\Leftrightarrow \frac{\alpha^2\cdot(r_B+4\cdot r_R)}{4\cdot\sqrt{\sigma^2\cdot r_R}} > \frac{\sqrt{r_R\cdot\sigma^2}}{\left(\sqrt{\frac{r_B+4\cdot r_R}{r_B}}-1\right)\cdot\frac{r_B\cdot\sigma^2}{\alpha^2}+\sqrt{\frac{r_B+4\cdot r_R}{r_B}}}$$

$$\Leftrightarrow \sigma^2\cdot\left((r_B+4\cdot r_R)\cdot\left(\sqrt{\frac{r_B+4\cdot r_R}{r_B}}-1\right)\cdot r_B - 4\cdot r_R\right) + \alpha^2\cdot(r_B+4\cdot r_R)\cdot\sqrt{\frac{r_B+4\cdot r_R}{r_B}} > 0,$$

which is not conclusive; thus,

$$\frac{\partial\sigma^2_{eff,d}}{\partial r_R} < 0 \quad \forall k:\ \sqrt{k}\in\left[0,\ \min\left\{\omega_4^d;\omega_0^d\right\}\right)$$

$$\frac{\partial\sigma^2_{eff,d}}{\partial r_R} > 0 \quad \forall k:\ \sqrt{k}\in\left(\min\left\{\omega_4^d;\omega_0^d\right\},\ \omega_0^d\right].$$

| | $\frac{\partial}{\partial r_B}$ | $\frac{\partial}{\partial r_R}$ | $\frac{\partial}{\partial k}$ | $\frac{\partial}{\partial \alpha}$ | $\frac{\partial}{\partial \sigma^2}$ |
|---|---|---|---|---|---|
| $e$ | $< 0$ | $< 0$ | $< 0$ | $> 0$ | $< 0$ |
| $m$ | $> 0 \;\; \forall k: \sqrt{k} \in \left[0,\;\; \min\left\{\omega_2^d;\omega_0^d\right\}\right)$ <br> $< 0 \;\; \forall k: \sqrt{k} \in \left(\min\left\{\omega_2^d;\omega_0^d\right\},\;\; \omega_0^d\right]$ | $> 0 \;\; \forall k: \sqrt{k} \in \left[0,\;\; \min\left\{\omega_1^d;\omega_0^d\right\}\right)$ <br> $< 0 \;\; \forall k: \sqrt{k} \in \left(\min\left\{\omega_1^d;\omega_0^d\right\},\;\; \omega_0^d\right]$ | $< 0$ | $> 0$ | $> 0 \;\; \forall k: \sqrt{k} \in \left[0,\;\; \min\left\{\omega_3^d;\omega_0^d\right\}\right)$ <br> $< 0 \;\; \forall k: \sqrt{k} \in \left(\min\left\{\omega_3^d;\omega_0^d\right\},\;\; \omega_0^d\right]$ |
| $a_B$ | $< 0$ | $< 0$ | $< 0$ | $> 0$ | $< 0$ |
| $a_R$ | $> 0 \;\; \forall k: \sqrt{k} \in \left[0,\;\; \min\left\{\omega_2^d;\omega_0^d\right\}\right)$ <br> $< 0 \;\; \forall k: \sqrt{k} \in \left(\min\left\{\omega_2^d;\omega_0^d\right\},\;\; \omega_0^d\right]$ | $< 0$ | $< 0$ | $> 0$ | $< 0$ |
| $\Pi$ | $< 0$ | $< 0$ | $< 0$ | $> 0$ | $< 0$ |
| $\sigma_{eff}^2$ | $< 0 \;\; \forall k: \sqrt{k} \in \left[0,\;\; \min\left\{\omega_2^d;\omega_0^d\right\}\right)$ <br> $> 0 \;\; \forall k: \sqrt{k} \in \left(\min\left\{\omega_2^d;\omega_0^d\right\},\;\; \omega_0^d\right]$ | $< 0 \;\; \forall k: \sqrt{k} \in \left[0,\;\; \min\left\{\omega_4^d;\omega_0^d\right\}\right)$ <br> $> 0 \;\; \forall k: \sqrt{k} \in \left(\min\left\{\omega_4^d;\omega_0^d\right\},\;\; \omega_0^d\right]$ | $> 0$ | $< 0$ | $> 0$ |

**Tab. 3** **Comparative statics for optimal results under decentralization when the firm's outcome is available as a performance measure.** The first column of the table determines which output parameter is derived and analyzed with respect to the input parameter from the first row of the table. The additional bounds in cases in which the direction of the derivative differs for low and high risk-management effort cost, are defined in the Appendix A8.

### A9. Proof of Proposition 2

From a comparison of (8d) and (11d), the following is straightforward:

$$\Delta_{a_R^d - a_R^c} = a_R^d - a_R^c = \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} - \frac{1}{2} \cdot \sqrt{\frac{r_B}{r_R}} + \frac{r_B}{\alpha^2} \cdot \sqrt{\frac{k \cdot \sigma^2}{r_R}} \cdot \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} \ ,$$

$$\Delta_{a_R^d - a_R^c} < 0 \Leftrightarrow \sqrt{k} < \left( \frac{\sqrt{r_B + 4 \cdot r_R}}{2} - \sqrt{r_R} \right) \cdot \frac{\alpha^2}{r_B \cdot \sqrt{\sigma^2}} \equiv \omega_{a_R^d - a_R^c} \ .$$

We need to compare the new restriction with the original bounds, which is not conclusive; thus,

$$a_R^d < a_R^c \quad \forall k: \ \sqrt{k} \in \left[ 0, \ \min\left\{ \omega_{a_R^d - a_R^c}; \omega_0^c; \omega_0^d \right\} \right)$$

$$a_R^d > a_R^c \quad \forall k: \ \sqrt{k} \in \left( \min\left\{ \omega_{a_R^d - a_R^c}; \omega_0^c; \omega_0^d \right\}, \ \min\left\{ \omega_0^c; \omega_0^d \right\} \right].$$

The effect transitions to risk-management effort. Comparing (8c) and (11c), we derive

$$\Delta_{m^d - m^c} = \left( \sqrt{\frac{r_R}{r_B + 4 \cdot r_R}} - \frac{1}{2} + \sqrt{\frac{r_B}{r_B + 4 \cdot r_R}} \cdot \frac{\sqrt{r_B \cdot k \cdot \sigma^2}}{\alpha^2} \right) \cdot \sqrt{\frac{r_B \cdot \sigma^2}{k}} \ ,$$

$$\Delta_{m^d - m^c} < 0 \Leftrightarrow \sqrt{k} < \omega_{a_R^d - a_R^c} \ ,$$

$$m^d < m^c \quad \forall k: \ \sqrt{k} \in \left[ 0, \ \min\left\{ \omega_{a_R^d - a_R^c}; \omega_0^c; \omega_0^d \right\} \right)$$

$$m^d > m^c \quad \forall k: \ \sqrt{k} \in \left( \min\left\{ \omega_{a_R^d - a_R^c}; \omega_0^c; \omega_0^d \right\}, \ \min\left\{ \omega_0^c; \omega_0^d \right\} \right].$$

For the effective variance, the inverse is true with:

$$\sigma_{eff,d}^2 > \sigma_{eff,c}^2 \quad \forall k: \ \sqrt{k} \in \left[ 0, \ \min\left\{ \omega_{a_R^d - a_R^c}; \omega_0^c; \omega_0^d \right\} \right)$$

$$\sigma_{eff,d}^2 < \sigma_{eff,c}^2 \quad \forall k: \ \sqrt{k} \in \left( \min\left\{ \omega_{a_R^d - a_R^c}; \omega_0^c; \omega_0^d \right\}, \ \min\left\{ \omega_0^c; \omega_0^d \right\} \right].$$

### A10. Proof of Proposition 3

From a comparison of (8b) and (11b), the following is straightforward:

$$\Delta_{a_B^d - a_B^c} = a_B^d - a_B^c = \underbrace{\left( 2\cdot\sqrt{r_B} - \left( \sqrt{\frac{r_B + 4\cdot r_R}{r_B}} - 1 \right) \cdot \frac{r_B}{\sqrt{r_R}} \right)}_{>0} \cdot \frac{\sqrt{k\cdot\sigma^2}}{\alpha^2} > 0 .$$

From a comparison of (8f) and (11f), the following is straightforward:

$$\Delta_{\Pi^d - \Pi^c} = \Pi^d - \Pi^c = \frac{\sqrt{k\cdot\sigma^2}}{2} \cdot \left( 2\cdot\sqrt{r_B} - \left( \sqrt{\frac{r_B + 4\cdot r_R}{r_B}} - 1 \right) \cdot r_B \cdot \sqrt{\frac{1}{r_R}} \right) \cdot \left( a_B^d + a_B^c \right),$$

$$\Delta_{\Pi^d - \Pi^c} > 0 \Leftrightarrow 2\cdot\sqrt{r_B \cdot r_R} + r_B - \sqrt{\frac{r_B + 4\cdot r_R}{r_B}} \cdot r_B > 0 \Leftrightarrow 2\cdot\sqrt{\frac{4\cdot r_R}{r_B}} > 0 \; .$$

## A11. Relevant bounds for first-best solution

For the risk-management effort to exist, the following must be true:

$$\left(1-\frac{r_R \cdot r_P \cdot \rho^2}{2 \cdot r_B \cdot r_R + r_P \cdot r_R - r_B^2}\right) \cdot \frac{r_P}{2 \cdot k \cdot pr_x} > 0 \Leftrightarrow r_P > \frac{r_B \cdot \left(r_B - 2 \cdot r_R\right)}{r_R \cdot \left(1-\rho^2\right)}.$$

For first best risk-management effort to exist, the board or the RM must be sufficiently risk averse.

Moreover, the productive effort is non-negative as long as the productive incentives are non-negative, thus:

$$a_B^{FB} \geq 0 \Leftrightarrow \frac{r_R \cdot r_P \cdot \rho}{2 \cdot r_B \cdot r_R + r_P \cdot r_R - r_B^2} \cdot \sqrt{\frac{pr_y}{pr_x}} \geq 0 \Leftrightarrow r_P \geq \frac{r_B \cdot \left(r_B - 2 \cdot r_R\right)}{r_R}.$$

As $1-\rho^2 < 1$ is the first restriction which is always more restrictive than the second one and thus productive incentives are always positive.

Finally, for the risk-management effort to be profitable, the following must be true:

$$m^{FB} \geq 1 \Leftrightarrow k \leq \left(1-\frac{r_R \cdot r_P \cdot \rho^2}{2 \cdot r_B \cdot r_R + r_P \cdot r_R - r_B^2}\right) \cdot \frac{r_P}{2 \cdot pr_x}.$$

## A12. Derivation of the second-best solution

Certainty equivalent of the RM is defined as follows:

$$CE_R = a_R \cdot e + b_R - k \cdot m - \frac{1}{2} \cdot r_R \cdot a_R^2 \cdot \frac{\sigma_y^2}{m}.$$

Deriving for *m* gives the optimal decision of the RM regarding her/his effort:

$$\frac{\partial CE_B}{\partial m} = -k + \frac{1}{2} \cdot r_R \cdot a_R^2 \cdot \frac{\sigma_y^2}{m^2} \overset{!}{=} 0 \Leftrightarrow m = a_R \cdot \sqrt{\frac{r_R}{2 \cdot pr_y \cdot k}}.$$

Certainty equivalent of the BUM, under individual rationality and incentive constraint of the RM, is formulated in the following way:

$$CE_B = a_B \cdot e + b_B - \frac{1}{2} \cdot e^2 - \left( \left( r_B + 2 \cdot r_R \right) \cdot a_R + r_B \cdot \frac{a_B^2}{a_R} - 2 \cdot r_B \cdot a_B \right) \cdot \sqrt{\frac{k \cdot \sigma_y^2}{2 \cdot r_R}}.$$

Derivation allows arrival at an optimal decision of the BUM:

$$\frac{\partial CE_B}{\partial e} = a_B - e \overset{!}{=} 0 \Leftrightarrow e = a_B \ ,$$

$$\frac{\partial CE_B}{\partial a_R} = -\left( \left( r_B + 2 \cdot r_R \right) - r_B \cdot \left( \frac{a_B}{a_R} \right)^2 \right) \cdot \sqrt{\frac{k \cdot \sigma_y^2}{2 \cdot r_R}} \overset{!}{=} 0 \Leftrightarrow a_R = a_B \cdot \sqrt{\frac{r_B}{2 \cdot r_R + r_B}}.$$

Thus, the board's utility, under individual rationality and incentive constraints of the BUM:

$$CE_P = a_B \cdot \left( 1 - \left( \left( 2 \cdot r_B + r_P \right) \cdot \sqrt{\frac{2 \cdot r_R + r_B}{r_B}} - 2 \cdot r_B \right) \cdot \sqrt{\frac{k}{2 \cdot pr_y \cdot r_R}} \right)$$
$$- \frac{1}{2} \cdot a_B^2 - r_P \cdot \sqrt{\frac{pr_y \cdot k \cdot \left( 2 \cdot r_R + r_B \right)}{2 \cdot r_B \cdot r_R}} \cdot \left( \frac{1}{a_B \cdot pr_x} - \frac{2 \cdot \rho}{\sqrt{pr_y \cdot pr_x}} \right).$$

Derivation implicitly leads to an optimal decision of the firm board with regard to the BUM's incentives:

$$\frac{\partial CE_P}{\partial a_B} = \left( 1 - \left( \left( 2 \cdot r_B + r_P \right) \cdot \sqrt{\frac{2 \cdot r_R + r_B}{r_B}} - 2 \cdot r_B \right) \cdot \sqrt{\frac{k}{2 \cdot pr_y \cdot r_R}} \right)$$
$$- a_B - r_P \cdot \sqrt{\frac{pr_y \cdot k \cdot \left( 2 \cdot r_R + r_B \right)}{2 \cdot r_B \cdot r_R}} \cdot \left( - \frac{1}{a_B^2 \cdot pr_x} \right) \overset{!}{=} 0.$$

I need to solve a polynomial equation with regard to the BUM's incentives:

$$a_B^3 - a_B^2 \cdot \left( 1 - \left( \left( 2 \cdot r_B + r_P \right) \cdot \sqrt{\frac{2 \cdot r_R + r_B}{r_B}} - 2 \cdot r_B \right) \cdot \sqrt{\frac{k}{2 \cdot pr_y \cdot r_R}} \right) - \sqrt{\frac{pr_y \cdot k \cdot \left( 2 \cdot r_R + r_B \right)}{2 \cdot r_B \cdot r_R}} \cdot \frac{r_P}{pr_x} = 0.$$

The discriminant of this equation is defined in the following way:

$$\Delta = \begin{pmatrix} 4\cdot\left(1-\left(\left(2\cdot r_B + r_P\right)\cdot\sqrt{\frac{2\cdot r_R + r_B}{r_B}} - 2\cdot r_B\right)\cdot\sqrt{\frac{k}{2\cdot pr_y\cdot r_R}}\right)^3 \\ +27\cdot\sqrt{\frac{pr_y\cdot k\cdot\left(2\cdot r_R + r_B\right)}{2\cdot r_B\cdot r_R}}\cdot\frac{r_P}{pr_x} \end{pmatrix}\cdot 27\cdot\sqrt{\frac{pr_y\cdot k\cdot\left(2\cdot r_R + r_B\right)}{2\cdot r_B\cdot r_R}}\cdot\frac{r_P}{pr_x}.$$

The discriminant is non-negative when $\sqrt{k}$ is sufficiently low. Then, only one solution exists. For higher $\sqrt{k}$ values, the discriminant is negative and there are three possible solutions. For more precise bounds,

I solve a further polynomial equation for $\sqrt{k}$:

$$\left(\left(2\cdot r_B + r_P\right)\cdot\sqrt{\frac{2\cdot r_R + r_B}{r_B}} - 2\cdot r_B\right)^3\cdot\left(\sqrt{\frac{1}{2\cdot pr_y\cdot r_R}}\right)^3\cdot\sqrt{k}^3$$

$$-3\cdot\left(\left(2\cdot r_B + r_P\right)\cdot\sqrt{\frac{2\cdot r_R + r_B}{r_B}} - 2\cdot r_B\right)^2\cdot\left(\sqrt{\frac{1}{2\cdot pr_y\cdot r_R}}\right)^2\cdot\sqrt{k}^2$$

$$+3\cdot\left(\left(\left(2\cdot r_B + r_P\right)\cdot\sqrt{\frac{2\cdot r_R + r_B}{r_B}} - 2\cdot r_B\right)\cdot\sqrt{\frac{1}{2\cdot pr_y\cdot r_R}} - \frac{9}{4}\cdot\sqrt{\frac{pr_y\cdot\left(2\cdot r_R + r_B\right)}{2\cdot r_B\cdot r_R}}\cdot\frac{r_P}{pr_x}\right)\cdot\sqrt{k} - 1 \le 0.$$

Discriminant is necessary:

$$\Delta_k = \left(\left(2\cdot r_B + r_P\right)\cdot\sqrt{\frac{2\cdot r_R + r_B}{r_B}} - 2\cdot r_B\right)^{10}\cdot\left(\sqrt{\frac{1}{2\cdot pr_y\cdot r_R}}\right)^{10}\cdot\frac{531441\cdot\left(2\cdot r_R + r_B\right)\cdot pr_y\cdot r_P^2}{32\cdot r_R\cdot r_B\cdot pr_x^2}$$

$$\cdot\left(1-\frac{\sqrt{\frac{2\cdot r_R + r_B}{r_B}}\cdot\frac{pr_y\cdot r_P}{pr_x}}{\left(2\cdot r_B + r_P\right)\cdot\sqrt{\frac{2\cdot r_R + r_B}{r_B}} - 2\cdot r_B}\right).$$

When the risk aversion of the BUM is sufficiently high (higher than the one of the principal), the determinant of the polynomial equation for $\sqrt{k}$ is positive:

$$1-\frac{\sqrt{\frac{2\cdot r_R + r_B}{r_B}}\cdot\frac{pr_y\cdot r_P}{pr_x}}{\left(2\cdot r_B + r_P\right)\cdot\sqrt{\frac{2\cdot r_R + r_B}{r_B}} - 2\cdot r_B} \ge 0 \Leftrightarrow r_P\cdot\left(\frac{pr_y}{pr_x} - 1\right) \le 2\cdot r_B\cdot\left(1-\sqrt{\frac{r_B}{2\cdot r_R + r_B}}\right).$$

I need to differentiate between two cases.

Case I:

$$\frac{pr_y}{pr_x} - 1 \geq 0 \Leftrightarrow pr_y \geq pr_x,$$

thus, PM is more precise than the firm’s outcome in measuring managers’ performance. Then

$$\Rightarrow r_P \leq \frac{2 \cdot r_B \cdot pr_x \cdot \left(1 - \sqrt{\frac{r_B}{2 \cdot r_R + r_B}}\right)}{pr_y - pr_x},$$

thus, only one real solution for $\sqrt{k}$ exists if and only if the board is generally not very risk averse.

Case II:

$$\frac{pr_y}{pr_x} - 1 < 0 \Leftrightarrow pr_y < pr_x,$$

thus, PM is less precise than the firm’s outcome in measuring managers’ performance. Then

$$\Rightarrow r_P \geq \frac{2 \cdot r_B \cdot pr_x \cdot \left(1 - \sqrt{\frac{r_B}{2 \cdot r_R + r_B}}\right)}{pr_y - pr_x},$$

which is always true, as the right side of the equation is always negative. Thus, no further restriction on the board’s risk aversion is necessary and only one real solution for $\sqrt{k}$ exists.

In both cases, if the restrictions are fulfilled, for the original discriminant the following is true:

$$\Delta \geq 0 \Leftrightarrow \sqrt{k} \leq \omega_0$$

$$\Delta < 0 \Leftrightarrow \sqrt{k} > \omega_0,$$

where

$$\omega_0 = \left(1 + \left(\sqrt[6]{\frac{729 \cdot pr_y^2 \cdot (2 \cdot r_R + r_B) \cdot r_P^2}{64 \cdot r_B \cdot pr_x^2 \cdot \left((2 \cdot r_B + r_P) \cdot \sqrt{\frac{2 \cdot r_R + r_B}{r_B}} - 2 \cdot r_B\right)^2}} \cdot \left(\sqrt[3]{1 + \sqrt{1 - \frac{pr_y \cdot r_P}{pr_x \cdot \left((2 \cdot r_B + r_P) - 2 \cdot r_B \cdot \sqrt{\frac{r_B}{2 \cdot r_R + r_B}}\right)}}} + \sqrt[3]{1 - \sqrt{1 - \frac{pr_y \cdot r_P}{pr_x \cdot \left((2 \cdot r_B + r_P) - 2 \cdot r_B \cdot \sqrt{\frac{r_B}{2 \cdot r_R + r_B}}\right)}}}\right)\right)\right) \cdot \frac{\sqrt{2 \cdot pr_y \cdot r_R}}{(2 \cdot r_B + r_P) \cdot \sqrt{\frac{2 \cdot r_R + r_B}{r_B}} - 2 \cdot r_B}.$$

Summing up, if the cost of the risk-management effort is not too high and the performance measure is either more precise than the firm's outcome with the firm's board not too risk-averse or less precise than the firm's outcome, there is only one real result:

$$a_B = \frac{1}{12 \cdot H} \cdot \left( 1 + \sqrt[3]{1 + \frac{J}{2 \cdot H^3} \cdot \left( 1 + \sqrt{1 + \frac{4 \cdot H^3}{J}} \right)} + \sqrt[3]{1 + \frac{J}{2 \cdot H^3} \cdot \left( 1 - \sqrt{1 + \frac{4 \cdot H^3}{J}} \right)} \right),$$

with

$$J = 27 \cdot \sqrt{\frac{pr_y \cdot k \cdot (2 \cdot r_R + r_B)}{2 \cdot r_B \cdot r_R}} \cdot \frac{r_P}{pr_x} \text{ and } H = \left( 1 - \left( (2 \cdot r_B + r_P) \cdot \sqrt{\frac{2 \cdot r_R + r_B}{r_B}} - 2 \cdot r_B \right) \cdot \sqrt{\frac{k}{2 \cdot pr_y \cdot r_R}} \right).$$

## A13. Relevant bounds for the second-best solution

First, I consider the restrictions resulting from the derivation of results.

Case I: $pr_y > pr_x$

$$\Rightarrow r_P \leq \frac{2 \cdot r_B \cdot pr_x \cdot \left(1 - \sqrt{\frac{r_B}{2 \cdot r_R + r_B}}\right)}{pr_y - pr_x}.$$

Case II: $pr_y < pr_x$ , no restrictions on $r_P$.

In both cases there is also a restriction on $k$ necessary:

$\sqrt{k} \leq \omega_0$ .

Moreover, the effort must be non-negative:

$e^{y,SB} \geq 0 \Leftrightarrow a_B^{y,SB} \geq 0,$

thus necessary:

$a_B^{y,SB} \geq 0.$

Similar to the case of contractible firm's outcome, as the organizations prefer the agents with low effort costs, only the first case is further analyzed, the relevant restriction being:

$$\sqrt{k} < \frac{\sqrt{2 \cdot pr_y \cdot r_R}}{(2 \cdot r_B + r_P) \cdot \sqrt{\frac{2 \cdot r_R + r_B}{r_B}} - 2 \cdot r_B} \equiv \omega_1,$$

which is more restrictive than the other restriction and thus the relevant restriction.

Finally, for the risk-management effort to be profitable, the following must be true:

$$m^{y,SB} \geq 1 \Leftrightarrow a_B^{y,SB} \cdot \sqrt{\frac{r_B \cdot r_R}{2 \cdot pr_y \cdot (2 \cdot r_R + r_B) \cdot k}} \geq 1.$$

The last restriction on the cost of the risk-management effort is only implicitly given and is further denoted as $\omega_2$ .

Overall, binding is the lowest of the restrictions: $\sqrt{k} \leq \min\{\omega_1; \omega_2\}$ .

## A14. Second-best solution in case of a risk-neutral board

$$a_B^{SB,r_P=0} = 1 - r_B \cdot \left( \sqrt{\frac{2 \cdot r_R + r_B}{r_B}} - 1 \right) \cdot \sqrt{\frac{2 \cdot k}{pr_y \cdot r_R}}$$

$$a_R^{SB,r_P=0} = a_B^{SB,r_P=0} \cdot \sqrt{\frac{r_B}{2 \cdot r_R + r_B}}$$

$$m^{SB,r_P=0} = a_R^{SB,r_P=0} \cdot \sqrt{\frac{r_R}{2 \cdot pr_y \cdot k}} = a_B^{SB,r_P=0} \cdot \sqrt{\frac{r_B \cdot r_R}{(2 \cdot r_R + r_B) \cdot 2 \cdot pr_y \cdot k}}$$

$$e^{SB,r_P=0} = a_B^{SB,r_P=0}$$

$$CE_P^{SB,r_P=0} = \frac{1}{2} \cdot \left( a_B^{SB,r_P=0} \right)^2 = \frac{1}{2} \cdot \left( 1 - r_B \cdot \left( \sqrt{\frac{2 \cdot r_R + r_B}{r_B}} - 1 \right) \cdot \sqrt{\frac{2 \cdot k}{pr_y \cdot r_R}} \right)^2$$

$$\sigma^2_{PM,SB,r_P=0} = \frac{\sigma_y^2}{m^{SB,r_P=0}} = \frac{1}{pr_y \cdot m^{SB,r_P=0}}$$

$$\sigma^2_{F,SB,r_P=0} = \frac{\sigma_x^2}{m^{SB,r_P=0}} = \frac{1}{pr_x \cdot m^{SB,r_P=0}}$$

### A15. Relevant bounds for the second-best solution in case of risk-neutral board

The productive effort must be non-negative:

$$e^{SB} \geq 0 \Leftrightarrow \sqrt{k} \leq \frac{\sqrt{2 \cdot pr_y \cdot r_R}}{2 \cdot r_B \cdot \left(\sqrt{\frac{2 \cdot r_R + r_B}{r_B}} - 1\right)}.$$

Furthermore, for the risk-management effort to be profitable, the following must be true:

$$m^{SB} > 1 \Leftrightarrow \sqrt{k} < \frac{\sqrt{\frac{r_B \cdot r_R \cdot \sigma_y^2}{(2 \cdot r_R + r_B) \cdot 2}}}{1 + r_B \cdot \sigma_y^2 \cdot \left(1 - \sqrt{\frac{r_B}{2 \cdot r_R + r_B}}\right)}.$$

Binding is the most restrictive bound, thus:

$$\sqrt{k} < \frac{\sqrt{\frac{r_B \cdot r_R \cdot \sigma_y^2}{(2 \cdot r_R + r_B) \cdot 2}}}{1 + r_B \cdot \sigma_y^2 \cdot \left(1 - \sqrt{\frac{r_B}{2 \cdot r_R + r_B}}\right)} \equiv \omega_0^{r^P = 0}.$$

## A16. Bounds for comparative statics of the second-best solution in case of a risk-neutral board

$$\omega_1^{r_P=0} = \frac{1}{\left(\sqrt{r_B \cdot (2 \cdot r_R + r_B)} - 2 \cdot r_B\right) \cdot \left(2 + \frac{r_B}{r_R}\right) - 2 \cdot r_B} \cdot \sqrt{\frac{r_R}{2 \cdot \sigma_y^2}}$$

$$\omega_2^{r_P=0} = \frac{1}{\sqrt{2 \cdot r_R + r_B} - \sqrt{r_B}} \cdot \sqrt{\frac{r_R}{r_B \cdot 8 \cdot \sigma_y^2}}$$

$$\omega_3^{r_P=0} = \sqrt{\frac{r_R^3}{2 \cdot \sigma_y^2}} \cdot \left(\sqrt{\frac{2 \cdot r_R + r_B}{r_B}} \cdot \left((2 \cdot r_R + r_B)^2 - r_B \cdot r_R\right) - (2 \cdot r_R + r_B)^2\right)^{-1}$$

$$\omega_4^{r_P=0} = \sqrt{\frac{2 \cdot (r_R)^3}{r_B \cdot \sigma_y^2 \cdot (2 \cdot r_R + r_B)^3}} \cdot \frac{1}{2} \cdot \left(\frac{1}{2 \cdot r_R} - \sqrt{\frac{r_B}{(2 \cdot r_R + r_B)^3}} \cdot (1 + r_R)\right)^{-1}$$

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Mir ist bekannt, dass Unwahrheiten hinsichtlich der vorstehenden Versicherung die Zulassung zur Promotionsprüfung ausschließen und im Falle eines späteren Bekanntwerdens die Promotionsprüfung für ungültig erklärt werden oder der Doktorgrad aberkannt werden kann.

Göttingen, den 26. November 2021

(Marta Michaelis)

## Erklärung zum Eigenanteil der Dissertationsschrift

| | |
|---|---|
| Dissertationstitel: | „Organization and incentivization of risk management” |
| Autorin: | Marta Elżbieta Michaelis aus Tychy |
| Erstbetreuer: | Prof. Dr. Stefan Dierkes, Professur für Finanzen und Controlling |

**Paper 1:** **„Third-party monitoring and risk management: literature review”**

Alleinautorenschaft

**Paper 2:** **„Organizational design of risk management”**

Koautorenschaft mit folgenden Anteilen:

Marta Michaelis: Literaturrecherche, Berechnung des Models, Erstellung des Manuskriptes (überwiegend), Erstellung der Tabellen und Abbildungen

Stefan Dierkes: Konzeption des Models, Ergebnisdiskussion, Erstellung des Manuskriptes (Einleitung, Diskussion)

**Paper 3:** **„Performance measurement in firms with decentralized risk management and risk-averse board”**

Alleinautorenschaft

Göttingen, den 26. November 2021

(Marta Michaelis)