Salience and Management-by-Exception

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Abstract

This paper studies a firm's organisational responses if its agents misevaluate information. If a manager overreacts to unusual events it may desirable for the firm to adopt the management practice *management-by-exception.* I develop a theoretical framework to study the technique and derive conditions under parsimonious assumptions for when it should be adopted. Moreover, I show how further assumptions can refine the model's predictions. The strategy is implemented by controlling the information which the manager receives. In fact, in the absence of information transmission and processing costs, it may be optimal to not send inherently valuable signals concerning the economy's state to the manager.

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1 Introduction

A recent empirical literature has uncovered large effects of differences in management on productivity. Bloom et al. (2017) find that management accounts for about a fifth of the variation in productivity across plants *within* U.S. firms. Similarly, Bruhn et al. (2018) report large effects of changes in management practices from a randomised controlled trial. Given the large potential benefits of sound management, a number of studies further attempt to tie back the adoption of different management techniques to CEO-, firm- and market-characteristics such as the manager's educational attainment (Bertrand and Schoar, 2003), governance structure (Bloom and Reenen, 2007) and product competition (Bloom et al., 2017). This article investigates a determinant that has so far received few attention: overvaluation of salient properties in managerial decision-making.

I consider firms that do not face conflicts of interest: two individuals, a manager (she) and an owner (he), attempt to maximise a common objective. The manager directly affects the firm's profit. In particular, she decides how to use scarce resources in order to adapt the firm's work processes to a changing productive environment. Information regarding the state of the economy, *per se*, is a valuable signal in doing so. However, the manager has a tendency to misevaluate this information when incorporating it into her decision-making by overemphasising salient events (see Section 2.1 for a discussion). This may lead to a misallocation of resources and, thus, a failure to maximise profits.

In this setting, it is impossible to achieve the first-best outcome implied by perfectly informed and non-biased managerial decision-making. But the owner may still pursue a second-best solution by deciding whether or not and, more precisely, to which degree to implement the management technique *management-by-exception* (see Section 2.2 for a discussion). He does so by merely varying the information available to the manager on the economy's state so that she is only briefed if exceptional occurrences arise. Restricting access to any information for comparatively usual events, the owner may eliminate the manager's psychological bias through evoking adherence to an *ex-ante* optimal plan, but he will also decrease the firm's adaptability. On the other hand, for comparatively exceptional events the owner may wish to forfeit the institutional rigidity and inform the manager of the unusual occurrences, however, at the cost of reintroducing the bias.

Investigating the owner's trade-off between a better informed and a less biased decision-making on behalf of the manager, as captured by the implementation of *management-by-exception*, shall be the main focus of this article. Under parsimonious assumptions, I first identify manager- and production-specific characteristics driving the adoption of this management practice (see Proposition 1). More fine-grained predictions can further be made if the state of the economy is assumed to be standard normally distributed: then, for all possible productive settings there exists a uniquely optimal way of defining what should constitute an "exception" in guiding managerial attention (see Proposition 2).

With this article, I make two major contributions. I formulate a possible organisational coping-strategy when workers within the firm are affected by psychological biases in valueing their options. My research thus aligns with the seminal work of Simon (1945) who places aspects of bounded rationality at the centre of the debate on how to optimally design organisations. While a host of other theoretical studies work in this tradition, they have so far largely been restricted to information transmission constraints as the sole imperfection in the agents' decision-making (see Dessein and Prat, 2016, for a review). In going beyond this, my research answers to recent mounting evidence suggesting that behaviourally biased valuation by top-managers is, in fact, a prevalent real-life phenomenon.

Moreover, I present a novel model providing a theoretical foundation for a firm's choice of whether to adopt *management-by-exception*. In Athey et al. (1994) the adoption of the technique is assumed while in Garicano (2000) and Beggs (2001) it is inextricably related with the presence of a hierarchy. The adoption of the technique is thus given apart from the unrealistic case of a firm with only workers and no managers. Also, all previous models feature some explicit or implicit costs of information transmission. I show that firms may benefit from implementing *management-by-exception* even in the absence of any such costs. By considering a different set of underlying drivers, I derive new comparative statics regarding the adoption choice of the technique as well as the structure of organisations more generally.

The implementation mechanism has some desirable properties. First, it can be installed by solely controlling the flows of information within the organisation. The solution is therefore applicable to settings with limited contractibility and verifiability of the manager's actions. Second, not only the adaptive actions on the task-level may respond to the local shocks, but also the organisational structure as represented by the communication channels. This is a relative novelty in the literature and central to the proposed exception-based procedure. Third and a key insight of the paper, the organisation can meet its goals more effectively by strictly decreasing the flow of information among its members, in example time spent in meetings or on writing reports.

1.1 Related Literature

The article should be read as complementary to the recent literature in team theory and organizational economics featuring imperfect agents. A host of studies using a similar functional setting that favours adaptation to local shocks have pointed out the desirability of institutional rigidities. Dessein et al. (2016) find that if there are explicit costs of coordination across tasks, it may be optimal to fix the firm's operations for a large number of its activities and focus attention on a small number of core-competencies. In Powell (2015), static bureaucratic rules prevent managers to engage in costly influence-activities in an attempt to shape the organisation's outcomes towards their personal goals. However, in both these models the communication channels and governance structures, respectively, cannot respond to the realisation of the shock-vector, precluding any chance of flexibility in the organisational framework and to *manage-by-exception* in particular.

Interestingly, the main trade-off in this paper—better information versus a less-biased decision-making—is essentially identical to that of Dessein (2002) while it is arrived at and resolved from two different angles. In Dessein (2002), a principal holds decision rights and decides whether to delegate or simply gather information from an agent that strategically communicates. In my paper, delegation is fixed to a manager who is naive towards the bias in her decision-making and therefore behaves non-strategically. It is then the principal who strategically chooses the amount of information supplied to the manager in order to favourably affect the outcome.

In spirit, this paper is closest to Dessein and Santos (2016) in dealing with optimal organisational responses to managers who are biased in their valuation of the economy's state towards certain tasks. In method, however, this article can best be understood as a team-theoretical, bounded-rationality take on Brocas and Carrillo (2007) where the decision of information-transmission versus -restriction is made with respect to the size of the local shocks instead of iterative revealing of noisy signals. As an interesting sidenote, this article shows that it is possible to relax the strict assumption of information being public by assuming both the distribution of shocks as well as the information-restriction device to be symmetric.

More generally speaking, my findings corroborate articles that are driven by explicit or implicit costs of information transmission or processing such as Sah and Stiglitz (1986), de Clippel et al. (2017) or Calvó-Armengol et al. (2015).

2 Discussion of related concepts

2.1 Salience and Behaviourally Biased Managers

There is ample evidence suggesting that the decision-making of top-managers is influenced by psychological factors. Malmendier and Tate (2005) show that measures of overconfidence predict investment decisions of Forbes 500 managers. Malmendier et al. (2011) and Bernile et al. (2017) find that even formative events long before the managers' careers start, such as exposure to economic or natural disasters, shape their strategies of corporate financing and risk-taking, respectively.

Some of these behavioural biases appear to work through how manager's incorporate information into their decision-making. In an early, impactful article, Ocasio (1997) cites the "saliency of issues and answers" (p. 195) as one of six main mechanisms governing management choices. The role of saliency in individual decision-making is a well-established psychological phenomenon and has received considerable attention from economics. It posits that people do not treat all information equally, but instead some attributes may involuntarily make some pieces of information "stand out" and cause them to subsequently receive a disproportionate weight in the decision-making (see Taylor and Fiske (1978) for a review in psychology and DellaVigna (2009) in economics).

A series of articles corroborate this view. Dittmar and Duchin (2016) show that personal experience has a stronger influence on a manager's later behaviour if it is gathered during a salient period in the career, while Gennaioli et al. (2016) attest that top CFOs overvalue recent observations when predicting earnings. Englmaier et al. (2017) offer evidence from a randomised controlled trial where they treat a number of managers with altered information designs regarding the incentive schemes while keeping actual compensation unchanged. They, too, argue that differences in behaviour stem from increased salience of certain dimensions of the productive process.

While Kőszegi and Szeidl (2013) formulate a model with a similar focus, I will closely follow Bordalo et al. (2013) in functionally capturing the manager's systematic bias (see Section 3.2.2 for the mathematical formulation). In their setup, it is those attributes that differ most strongly from what is considered as "usual" which gain salience. Results from Barber and Odean (2008) seemingly underpin this view. Studying individual stock traders, they find that "stocks experiencing high abnormal trading volume (...) and stocks with extreme one-day returns" (Barber and Odean, 2008, p. 785) are bought disproportionately much.

2.2 Management Practices

Management-by-Exception embodies a systematic decision-making procedure for evaluating and reacting to challenges encountered by an organisation. Bass (1990) provides a concise definition of the concept, stating a leader who manages by exception behaves as follows:

> *"Watches and searches for deviations from rules and standards, takes corrective action" (Bass, 1990, p. 22)*

The Business Dictionary (2018) elaborates further on this, defining *mangement-by-exception* as a

> *"Practice whereby only the information that indicates a significant deviation of actual results from the budgeted or planned results is brought*

to the management's notice. Its objective is to facilitate management's focus on really important tactical and strategic tasks."

The management literature usually distinguishes between *active management-by-exception* and *passive management-by-exception.* The second is conceptually close to *laisser faire leadership* where the leader prefers to remain inactive unless exceptional problems arise. This paper studies the former, as the manager will always take action within the model. As the crucial hallmark of the management technique I identify its information management, namely that the manager is only briefed on exceptional occurrences. Therefore, the benchmark to which the adoption of *management-by-exception* will be compared throughout the paper is the scenario where the manager is fully informed at all times.

The concept has long been subject to academic debate, with an early treatment of the general idea dating back to Towne (1886). It gained substantial prominence in the management literature since Bass (1990) included it as a core-characteristic of leadership in his extension of the transactional-transformational paradigm introduced by Burns (1978). In fact, Patterson et al. (1995) argue that "over the past decade there has probably not been a more dominant paradigm in leadership thought".

Management-by-Exception also enjoys widespread use in practice. Mackintosh (1978) reports that by the seventies the technique already enjoyed widespread use in a large variety of fields. Nowadays, it is one of seven core-principles of the *PRINCE2*-system, one of the world's most prevalent structured project management methods with over 1.4 million certified graduates[1] from a diverse array of countries and economic sectors (Axelos, 2016).

While the practice was developed with an intended application in business management, *management-by-exception* has recently received further interest from air traffic control and specifically the automation of unmanned aircraft. Unmanned aircraft is already widely used in military operations (Hottman and Sortland, 2006) and is "on the verge of taking flight alongside manned aircraft in the National Airspace System" (Liu et al., 2013, p. 424) - within the United States of America. Such aircraft may perform all necessary functions automatically while skilled personnel are ready on the ground to remotely take control over the machine if unusual circumstances arise. There appears to be a consensus in the relevant literature that a major bottleneck for a successful introduction of these systems lies in "defining the basis for switching levels of automation support to the human" (Dekker and Woods, 1999, p. 88) and that "an appropriate level of automation is critical to the safety and performance characteristics of [unmanned aircraft systems] design." (Liu et al., 2013, p. 425)

[1] Database freely accessible at `https://www.axelos.com/successful-candidates-register`, accessed 19th of July, 2018

Analogous to this, this article characterises *management-by-exception* as an interplay between *ex-ante* (before observing the current state of the world) and *ex-post* (after observing the current state of the world) modes of decision-making. Following Dessein et al. (2016), I borrow vocabulary from March and Simon (1958)[2] in identifying these two modes of decision-making as *management-by-plan* and *management-by-feedback*, respectively. Investigating the optimal, exception-based switching point between plan- and feedback-management shall, in fact, be the main interest of this study.

3 The Model

I posit a one-shot sequential-move principal-agent model[3] which I solve for a second-best solution by backward induction. Decision rights over the firm's operations are fixedly delegated to the agent (henceforth called the manager, *she*) who is the only one that may directly affect the firm's profits. However, she naively and irreversibly makes mistakes in incorporating information upon observing the state of the economy which introduces a systematic bias into her decision-making and causes her to potentially fail in maximising the firm's profits. The principal (henceforth called the owner, *he*), can influence the actions of the manager by controlling her access to information. In doing so, he faces a trade-off between a better informed manager versus a less-biased decision-making. Figure 1 shows the model's timeline.

[2](March and Simon, 1958, p.182) remark: *"We may label coordination based on pre-established schedules coordination by plan, and coordination that involves transmission of new information coordination by feedback."*

[3]I opt to model the two decision-makers within the organisation, the manager and the owner, as two separate individuals. This is, however, simply due to expositional convenience. Apart from their different action spaces in the model, the manager's role is to unconsciously be biased by psychological factors while the owner's role is to take this bias into account and take precautions in order to avoid adverse consequences arising from it. In the spirit of Thaler and Shefrin (1981), the inter-personal problem could equivalently be understood as an intra-personal problem of a single individual with two selves. Although the manager may be inherently unable to reverse her own tendency to misevaluate, she may be aware of it and put mechanisms into place in order to commit her future self to a restricted set of information.

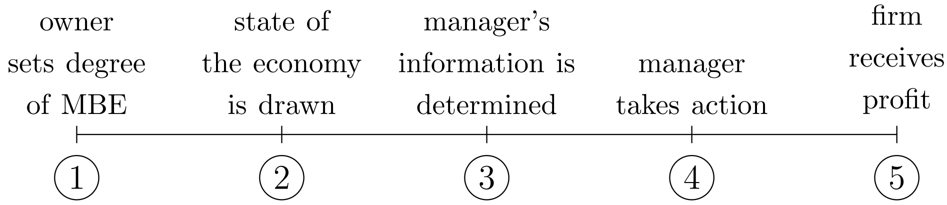


Figure 1: Timeline of the model.

I follow much of the relevant literature in assuming a tracking-cost framework as the functional setting (Dessein, 2002; Rantakari, 2008; Calvó-Armengol et al., 2015; Powell, 2015; Dessein et al., 2016). Moreover, I choose a team-theoretic setting where all individuals in the firm, the manager and the owner, attempt to maximise the firm's expected profits, although the manager's propensity to misevaluate signals may lead to a failure to do so. The firm earns profits π across two tasks indexed with i (,*e.g.* production and marketing):

$$\pi \equiv \sum_{i=1}^{2} \left[K_i - \beta_i \cdot |\theta_i - a_i(m(\omega))|^{\lambda}\right] \tag{1}$$

where K_i is a fix revenue for task i which, without loss of generality, is normalised to 0 for both i. θ_i are real numbers which are drawn from a single distribution with density function $g(\theta_i)$, β_i are strictly positive real numbers assigning *ex-ante* weights to the two tasks, λ is a strictly positive real number governing the curvature of the costs across both tasks. $m(\,\cdot\,)$ is the choice of the manager made on the basis of information ω, which translates into firm-level outcomes via a_1 and a_2.

The firm incurs costs according to the random task-level shocks θ_i. Throughout the article I will maintain the following assumptions:

Assumption 1. *Let the density function $g(\theta_i)$ be such that for any i*

(i) $E[\theta_i]$ exists

(ii) $g(\theta_i)$ is continuous

(iii) $g(\theta_i)$ is symmetric around 0.

It is the manager's role to shape the firm-level outcomes a_1 and a_2 by appropriately choosing $m(\omega)$ in order to avoid such costs. Thus, the firm's objective is to adapt as best as possible to changes in the productive environment.

3.1 The Owner

The owner cannot directly influence the profits of the firm. He can, however, affect the decision-making of the manager by deciding whether or not and, more precisely, to which degree to implement the management technique *management-by-exception* (see Section 2.2 for a discussion). He does so by purposefully controlling the amount of information available to the manager, denoted by $\omega \in \Omega$. At all times ω contains at least the following information: *(a)* the profit function π, including full knowledge of the parameters β_1, β_2 and λ, *(b)* all available information on the density function of the task-level shocks $g(\theta_i)$ and *(c)* the structure of the problem.[4] This fundamental set of information is denoted with $\overline{\omega}$.

The manager will then either remain with her fundamental knowledge $\overline{\omega}$ or she will additionally receive full information on the task-level shocks θ_1 and θ_2. This hinges on the owner's choice of implementing *management-by-exception*. If he does not adopt the practice, the manager will always receive full information on the state of the economy. If, on the other hand, he does, the manager will only receive the additional information once exceptional circumstances arise. I model this via the owner setting a real number $z \in [0, \infty)$. This choice affects the information available to the manager in the following way.

$$\omega = \begin{cases} \overline{\omega} & \text{if } |\theta_1| \wedge |\theta_2| < z \\ \overline{\omega} \cup \binom{\theta_1}{\theta_2} & \text{if } |\theta_1| \vee |\theta_2| > z \end{cases}$$

If the realisation for at least one of the realisations of the task-level shocks θ_1 or θ_2 deviates by more than z from their expected value (which by Assumption 1 is normalised to 0), the manager will receive full information on both values. In this case, events are sufficiently extreme to be considered an "exception". If, on the other hand, both realisations of the task-level shocks are sufficiently moderate so that neither of them deviate by more than z from their expected value, the manager receives no information on the state of the economy but instead makes her decisions on the basis of her fundamental knowledge $\overline{\omega}$. In this case, the firm concludes that no "exception" has occurred.

Given this characterisation, I identify the implementation of *management-by-exception* within the model as well as different degrees of it in the following way.

Definition 1. *The firm implements management-by-exception if the owner chooses any strictly positive value for z. Different values of z correspond to different degrees of management-by-exception being implemented, where lower values of z correspond to a more sensitive organisation and higher values of z to a more rigid organisation.*

[4] In the current setup, it makes no difference to the model's results whether and in how far the manager can observe the owner's action. I discuss this point after introducing the manager's action space in Section 3.3.

3.2 The Manager

The manager attempts to adapt the firm's operations to the productive environment. In order to add economic relevance to the problem, I implicitly assume that the firm has limited resources at its disposal so that the operations cannot be perfectly adapted to the state of the economy. The manager must therefore decide how to prioritise the firm's tasks when allocating these resources. I formalise this decision as a binary choice based on the manager's available information.

$$m : \Omega \to \{1, 2\} \tag{2}$$

This decision then translates into the firm-level outcomes a_i in the following way.

$$\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} (m(\omega)) := \begin{cases} \begin{pmatrix} \theta_1 \\ E[\theta] \end{pmatrix} & \text{if } m(\omega) = 1 \\ \begin{pmatrix} E[\theta] \\ \theta_2 \end{pmatrix} & \text{if } m(\omega) = 2 \end{cases}$$

Without intervention by the manager, work for both tasks is carried out doing "business-as-usual" by setting $a_1 = a_2 = E[\theta]$. The manager then improves on this outcome by either deciding to use scarce resources, such as having people work overtime or sending out a task-force, towards further adapting task $i = 1$ (by choosing $m(\omega) = 1$) or towards further adapting task $i = 2$ (by choosing $m(\omega) = 2$). For simplicity, I model the manager's options in a way that task-performance is perfectly adapted to the task-shocks or not at all. The model's focus hereby lies on examining the manager's problem to correctly prioritise the firm's tasks and ensure that resources are funnelled to where the benefits are the greatest. This evidently abstracts from potentially interesting "adaptation portfolios" the manager may wish to build, which may be an avenue for further research.

For the remainder of this section, I will charaterise the manager's modes of decision-making under the two feasible exposures to information: *ex-ante* (, *i.e.* without regard to the current state of the economy) and *ex-post* (, *i.e.* taking the current state of the economy into account). I follow the language of Dessein et al. (2016) in labelling these *management-by-plan* and *management-by-feedback*, respectively.

3.2.1 Management-by-plan

Definition 2. *The firm is managed by plan if the manager makes her decision solely on the basis of her fundamental knowledge such that* $\omega = \overline{\omega}$.

The manager would prefer to choose $m(\omega) = 1$ if and only if it yields higher profits than choosing $m(\omega) = 2$. Since under management-by-plan, by definition, the manager makes this decision without observing the local shocks θ_i, she must make her decision on the basis of the expected profits under each action.

$$\begin{aligned} E[-\beta_2 \cdot |\theta_2|^\lambda] &\geq E[-\beta_1 \cdot |\theta_1|^\lambda] \\ \gamma^{\frac{1}{\lambda}} E[|\theta_2|] &\leq E[|\theta_1|] \\ \iff \gamma &\leq 1 \end{aligned} \tag{3}$$

where I define $\gamma \equiv \frac{\beta_2}{\beta_1}$.

Assumption 2. *Without loss of generality, relabel β_1 and β_2 such that $\beta_1 \geq \beta_2$.*

Without observing the state-of-the economy, the manager will always choose to prioritise the task that carries the higher *ex-ante* weight. By construction, this coincides with task 1.

3.2.2 Management-by-feedback

Definition 3. *The firm is managed by feedback if the manager observes the state of the economy before making her decision such that $\omega = \overline{\omega} \cup \binom{\theta_1}{\theta_2}$.*

When managing by feedback, the manager does not have to form expectations over the state of the economy but can base her decision where to direct the organisational focus on the severity of the actual task-level shocks. However, when incorporating this information into her decision-making she misevaluates it. Particularly, she is psychologically biased towards salient events and, as a consequence, overweights extreme outcomes that differ strongly from the expected outcomes (see Section 2.1 for a further discussion on this).

I closely follow Bordalo et al. (2013) in capturing this functionally. I identify the reference-level for evaluating the task-level shocks with their expected value $E[\theta_i] = 0$ (see Assumption 1). Given a pair of realisations θ_1 and θ_2, the manager then inflates (deflates) the relative weight of the event that departed more (less) strongly from what was expected by a factor of $\frac{1}{\hat{\delta}}$ ($\hat{\delta}$). Hence, if she manages-by-feedback, she will choose to adapt task $i = 1$ if and only if

$$-\beta_2 \cdot \delta_2(\theta_1, \theta_2) \cdot |\theta_2|^\lambda \geq -\beta_1 \cdot \delta_1(\theta_1, \theta_2) \cdot |\theta_1|^\lambda \tag{4}$$

where

$$\delta_i(\theta_1, \theta_2) = \begin{cases} \hat{\delta} & \text{if } |\theta_i - E[\theta_i]| < |\theta_{-i} - E[\theta_{-i}]| \iff |\theta_i| < |\theta_{-i}| \\ 1 & \text{if } |\theta_i - E[\theta_i]| > |\theta_{-i} - E[\theta_{-i}]| \iff |\theta_i| > |\theta_{-i}| \end{cases}$$

where $0 < \hat{\delta} < 1$.

It is important to note that I assume the manager to be naive towards this bias, meaning that she is perfectly unaware of it and treats her subjective observations as truthful representations of the objective world.

3.3 Critical discussion

Although the owner can restrict the manager's access to information, it is important that he cannot fabricate or misrepresent it. Otherwise, the owner could anticipate the manager's bias and present the information in exactly such a way that the decision-bias and report-distortion would cancel each other out. Milgrom and Roberts (1986) have encountered the same issue in a delegation problem. I will follow them by assuming that, although information can be withheld, any information the manager does receive can be freely verified and/or there are sufficient penalties for lying.

The symmetry of the information restriction device around 0 mirrors the symmetry of the density function $g(\theta_i)$ (see Assumption 1). Hence, if in any given case the manager's information is, in fact, restricted and she must form expectations over the task-level shocks θ_i, she knows the density function's feasible support is symmetrically bounded. But even if she can perfectly observe the owner's choice of z, her unconditional expectation still remains her best bet for any possible z:

$$E[\theta_i|z] = E[\theta_i] \quad \forall z, \theta_i \quad \forall i \tag{5}$$

Therefore, the manager's reasoning specified in condition 3 still remains valid if she is aware of the fact that her information inflow is restricted in the manner described above.

Note that in this setting the manager also has no incentive to strategically threaten the owner with choosing a bad alternative in order to gain full information. First, the manager is unaware of her own decision-bias. She will thus expect the same judgement from the owner and interpret any attempts to restrict her information as a trembling-hand strategy. Second, any threats she might make in order to categorically ensure full information are incredible due to the game being one-shot and sequential. Once the owner has made his choice it is in the manager's best interest to attempt maximising profits given the information she has.

3.4 Construction of indirect profit function

Figure 2 depicts the manager's choice correspondence under all possible scenarios of the world. Anticipating this, the owner can express the expected profits as a tractable function of z. Due to the symmetry with respect to θ_1 and θ_2 of both

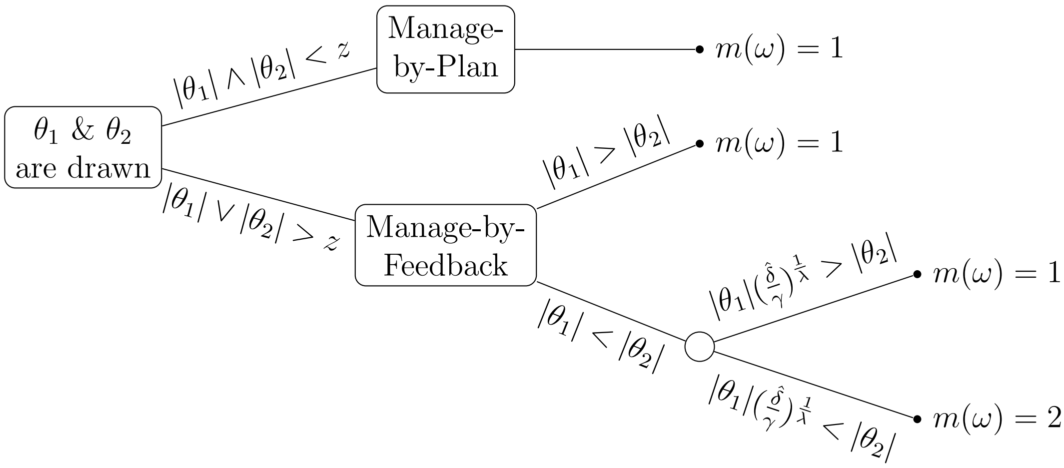


Figure 2: *Management-by-exception* implemented by flow of information. Under "normal" conditions, the manager adheres to the *ex-ante* optimal plan without regard to the state of the economy. If sufficiently unusual events occur, a briefing is called and the firm is managed by feedback.

the profit and the density function $g(\cdot)$ around 0, the bounds of the integrals can be mirrored arbitrarily around both θ_i-axes. We can thus restrict the focus of the investigation to positive values of θ_1 and θ_2. I arrive at the following expression:

$$\begin{aligned} E[\pi(z)] = 4 \cdot & \int_0^{\infty} \int_0^{max\{\left(\frac{\hat{\delta}}{\gamma}\right)^{\frac{1}{\lambda}} \cdot \theta_1, \theta_1\}} g(\theta_1) \cdot g(\theta_2) \cdot (-\beta_2 \theta_2^{\lambda}) \, \mathrm{d}\theta_2 \, \mathrm{d}\theta_1 \\ +4 \cdot & \int_0^{\infty} \int_{max\{\left(\frac{\hat{\delta}}{\gamma}\right)^{\frac{1}{\lambda}} \cdot \theta_1, \theta_1\}}^{\infty} g(\theta_1) \cdot g(\theta_2) \cdot (-\beta_1 \theta_1^{\lambda}) \, \mathrm{d}\theta_2 \, \mathrm{d}\theta_1 \\ +4 \cdot & \int_0^{min\{\left(\frac{\gamma}{\hat{\delta}}\right)^{\frac{1}{\lambda}} \cdot z, z\}} \int_{max\{\left(\frac{\hat{\delta}}{\gamma}\right)^{\frac{1}{\lambda}} \cdot \theta_1, \theta_1\}}^{z} g(\theta_1) \cdot g(\theta_2) \cdot (\beta_1 \theta_1^{\lambda} - \beta_2 \theta_2^{\lambda}) \, \mathrm{d}\theta_2 \, \mathrm{d}\theta_1 \end{aligned}$$

As Figure 2 shows, the manager only chooses to adapt task $i = 2$ if she manages-by-feedback and both $|\theta_1| < |\theta_2|$ and $|\theta_1|(\frac{\hat{\delta}}{\gamma})^{\frac{1}{\lambda}} < |\theta_2|$ hold. Of the latter two conditions, only one can be binding at any given time. For the sake of analytical simplicity, I can therefore replace the $min\{\cdot\}$- and $max\{\cdot\}$-operator by substituting the $\hat{\delta}$ in the expression above with the following parameter:

Definition 4. $\delta := max\{\gamma, \hat{\delta}\}$

Importantly, values for $\hat{\delta}$ lower than γ are not excluded from the analysis, but simply do not have any effect on it. I can then take the derivative of $E[\pi(z)]$ with respect to z. Applying Lebniz' Rule of Integration twice yields the following expression of the slope of the expected profits with respect to the implemented degree of *management-by-exception*:

$$\frac{\partial E[\pi(z)]}{\partial z} = 4 \cdot g(z) \cdot \int_0^{\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} z} g(\theta_1) \cdot (\beta_1 \theta_1^\lambda - \beta_2 z^\lambda) \, \mathrm{d}\theta_1 \tag{6}$$

4 Management-by-Exception as a Dominant Strategy

Following Bertrand and Schoar (2003), there has been a surge of interest in the financial and economic literature to explain the adoption choice of management styles and techniques by organisations and their effectiveness in practice (*e.g.* Bloom and Reenen, 2007; Benmelech and Frydman, 2015; Bloom et al., 2017). Long preceding this trend, extensive research efforts have been made in the management literature pursuing the same objective. Based on his extension of the transactional-transformational leadership paradigm introduced in Bass (1985), the author designed the *Multifactor Leadership Questionnaire* survey including tokens specifically designed to test for the implementation of *management-by-exception*. With more than 80 studies conducted using the survey-tool, a number of meta-analyses have attempted to empirically summarise the findings.

While these studies successfully uncover some stable relationships between management practices and measures of effectiveness, *management-by-exception* remains a "problem-child". (Judge and Piccolo, 2004, p. 755) state that *"management by exception (active and passive) was inconsistently related to the criteria"*. Similarly, (Lowe et al., 1996, p. 416) note that *"Management-by-Exception [was] inconsistent in [its] relationships with effectiveness across studies. Some research evidenced positive associations, while other findings showed a negative association"*.

In this section, I contribute to the discussion by theoretically mapping out relevant factors in the adoption choice of the management practice *management-by-exception*, yielding testable predictions while also potentially shedding light on earlier findings. To this end, I will conduct the investigation with an inherently binary view on the owner's action space by determining sufficient conditions when he will optimally choose a strictly positive value for z as opposed to choosing $z = 0$. By Definition 1 this corresponds to *management-by-exception* being implemented at least to some degree. Although this analysis lacks precision, it retains generality as it is done under the minimal assumptions specified in Assumption 1. In the following section I will show that maximum precision can be obtained with further assumptions on the distribution of the economy's state.

First, it is helpful to establish some properties of the following function:

$$k(z) \equiv \frac{z \cdot g((\frac{\gamma}{\delta})^{\frac{1}{\lambda}} z)}{\int_0^{(\frac{\gamma}{\delta})^{\frac{1}{\lambda}} z} g(\theta_1)\, \mathrm{d}\theta_1} \tag{7}$$

defined on the domain $z \in (0, \infty)$.

Lemma 1. *The function* k

(i) is continuous.

(ii) satisfies $\lim_{z\to 0} k(z) = \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}} \geq 1$.

Before proceeding, note that since the density function $g(\,\cdot\,)$ is, by Assumption 1, continuous and symmetric around 0, it holds that $4 \cdot g(z) > 0$ in the vicinity of $z = 0$. Therefore $\frac{\partial \pi}{\partial z} \geq 0$ if and only if

$$f(z) := \int_0^{(\frac{\gamma}{\delta})^{\frac{1}{\lambda}} z} g(\theta_1) \cdot (\beta_1 y_1^{\lambda} - \beta_2 z^{\lambda})\, \mathrm{d}\theta_1 \geq 0 \tag{8}$$

Characterising $f(z)$ is thus equivalent to characterising the gradient of the expected profits in the vicinity of $z = 0$. The following finding provides a tool for doing so.

Lemma 2. *For* $z > 0$ *and* $1 > \gamma > 0$, $f'(z) \geq 0$ *if and only if* $k(z) \geq \lambda \cdot \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}} \frac{\delta}{1-\delta}$.

Before deriving the main result, it is helpful to make two observations. First, by an application of the Combination Theorem for Continuous Functions, the slope of the profit function is continuous at all $z \in [0, \infty)$. Hence, although the function $k(z)$ is not defined at $z = 0$ itself, the function of main interest $\frac{\partial E[\pi(z)]}{\partial z}$ on which inferences are made is defined and well-behaved at this point. Second, note that $\frac{\partial E[\pi(z)]}{\partial z}|_{z=0} = 0$ for all feasible settings. Therefore, if the slope of the expected profits increases when increasing z from 0, it becomes positive. In this case, expected profits also rise by increasing z from $z = 0$, rendering $z = 0$ a dominated strategy. Using the insights from Lemma 1 and Lemma 2, I derive a simple condition for when this holds true.

Proposition 1. *For all distributions of the task-level shocks* θ_1 *and* θ_2 *satisfying Assumption 1 the firm adopts management-by-exception if* $\lambda \cdot \frac{\delta}{1-\delta} < 1$.

First, it is easy to verify a rather technical insight.

Corollary 1. *Management-by-exception is only adopted if there is a behavioural bias in the manager's decision-making ($\widehat{\delta} < 1$).*

This stems from the fact that, within the model, the manager's inclination to misevaluate her available information is the sole driver for implementing *management-by-exception*. Specifically, her behavioural bias causes her to misprioritise the firm's tasks and fail to direct the organisational focus to the most important areas. By effectively introducing rigid plans on *ex-ante* optimal strategies, the manager's misprioritisation through "over-responsiveness" can be reversed, however, at the cost of misprioritisation through "under-responsiveness". If for some ranges of moderate realisations of the task-level shocks θ_1 and θ_2 the first effect dominates the second, *management-by-exception* at least to some degree improves prioritisation and should thus be adopted.

As stated earlier, the model does not claim exclusiveness. There may well be further motivations for implementing the management technique, such as costly information transmission. It appears to be a relevant objective, though, since the practician (Mackintosh, 1978, p. 96) in the chapter *"Activating the system that spotlights the biggest problems"* concerning *management-by-exception* documents: *"Many times management will commit the entire company to a drive for the elimination of what it conceives to be major operating problems. All too often, however, these drives are initiated with inadequate or partial information (...), and result in little more than a futile, misguided expenditure of time and effort."*

Corollary 2. *Ceteris paribus, a stronger bias in the manager's decision making (lower $\widehat{\delta}$) makes an adoption of management-by-exception more likely.*

This result provides a possible explanation for some previous, puzzling empirical findings. It has long been surmised that *"in high-risk conditions where safety is of concern, active management-by-exception may play a more prominent and effective role"* (Antonakis et al., 2003, p. 270). Bass and Avolio (2000) corroborate this by studying the performance of U.S. Army platoons. They find large positive effects of *management-by-exception* on a unit's readiness. This may be a result of leaders finding it difficult to maintain a cold and objective decision-making in contexts that are fast-paced and potentially life-threatening. The more this is the case, the more they may benefit from rigid protocols that are followed irrespective of the situation's developments unless sufficiently exceptional circumstances arise.

Apart from contextual factors that may lead to the adoption of *management-by-exception*, there may be manager-specific determinants, too. (Antonakis et al., 2003, p. 274) remark that *"men tend to use management-by-exception more often than do women"*. It is a well-established finding that men are generally more overconfident than women (e.g. Barber and Odean, 2008). The stronger prevalence of the management technique may be due to mirroring, gender-specific phenomena regarding overreactions to salient stimuli.

Corollary 3. *Ceteris paribus, a stronger valuation of extreme events in the manager's decision making (higher λ) makes an adoption of management-by-exception less likely.*

Perhaps surprisingly, although *management-by-exception* appears to do well in dangerous, high-stake environments, a higher weight on extreme outcomes makes the technique less attractive for the firm. If outliers become more important, then a more sensitive policy (,*i.e.* a lower z) will be desired so that more events can be dealt with individually rather than via a rigid plan. Although some studies such as Bernile et al. (2017) tie back corporate policies to risk attitudes, surprisingly little research has been done examining the adoption choice of *management-by-exception* towards such sentiments.

Corollary 4. *Ceteris paribus, a stronger polarisation in the ex-ante importance across the firm's tasks (lower γ) makes an adoption of management-by-exception more likely.*

The desirability of *management-by-exception* increases if the *ex-ante* quality of the plan rises. To illustrate this point, consider a firm where $\beta_2 \to 0$ so that $\gamma \to 0$. It will then never be optimal for the manager to adapt task $i = 2$. *Management-by-plan* will then always select the best strategy, thus increasing the desirability of a highly rigid *management-by-exception* policy. This result reflects findings from Dessein et al. (2016). In a similar functional setting where there are limits on information transmission within the firm, the authors find that an increased *ex-ante* importance of already important tasks may make it desirable to make the organisation more rigid by managing more of the firm's tasks by plan. However, while in their setup this outcome is static and independent of the economy's state, under *management-by-exception* the firm will always revert to *management-by-feedback* if sufficiently exceptional circumstances arise.

Since with the *Multifactor Leadership Questionnaire* survey there already exists a highly common tool to elicit the model's main variable, the major challenge for empirical estimations of the model's predictions lies in identifying and constructing measures of the key parameters γ, $\hat{\delta}$ and λ. Firm's accounting posts of different divisions may provide proxies for imbalances of costs across their products' dimensions (γ). Concerning the remaining drivers, there is a large literature in linking the adoption of management practices to psychometric indicators of the leaders (see Bono and Judge, 2004, for a meta-analysis). Moreover, in 2015 the updated version of the large-scale *Management and Organizational Practices Survey* has acknowledged the importance of proper decision-making as well as utilising correct information inputs to do so by including the new section *data and decision-making*. In a similar vein, eliciting personal or contextual risk- and salience sentiments may prove insightful.

5 Existence and Uniqueness of Optimal Degree of Management-by-Exception

In recent years, *management-by-exception* has received interest towards applications in the automation of unmanned aircraft. Such aircraft may perform all necessary functions automatically while skilled personnel are ready on the ground to remotely take control over the machine if unusual circumstances arise. However, when practically implementing the system it has been observed that "defining the basis for switching levels of automation support to the human remains difficult" (Dekker and Woods, 1999, p. 88).

In fact, even though virtually all of the literature on *management-by-exception* agrees on the importance of establishing a plan that allows to identify exceptions, there only exists vague guidance on how such a system should be set up and calibrated. Experience-based rule-of-thumb and intuitive graphical analysis appear to be common methods in practice. To the best of my knowledge, there does not exist a rigorous theoretical foundation to answer a central question: *"What is an exception?"* (Dekker and Woods, 1999, p. 88)

In this section, I will show that in the given setting this question can be answered precisely if one is willing to place further assumptions on the distribution function of the state of the economy $g(\,\cdot\,)$.[5] For the remainder of the article I assume that the task-level shocks θ_1 and θ_2 are independently drawn from a standard normal distribution:

Assumption 3. *Let*

$$g(\theta_i) \equiv \frac{1}{\sqrt{2\pi}} e^{\frac{-\theta_i^2}{2}} \equiv \phi(\theta_i) \quad \forall i \tag{9}$$

As this assumption constitutes a special case of the previous set placed on the distribution of the task-level shocks (Assumption 1), all results from Proposition 1 still obtain under the current setting. However, it is now possible to derive additional properties of the function $k(z)$ (see Equation (7)).

Lemma 3. *The function* k

(i) is continuous.

(ii) satisfies $\lim_{z \to 0} k(z) = \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}} \geq 1.$

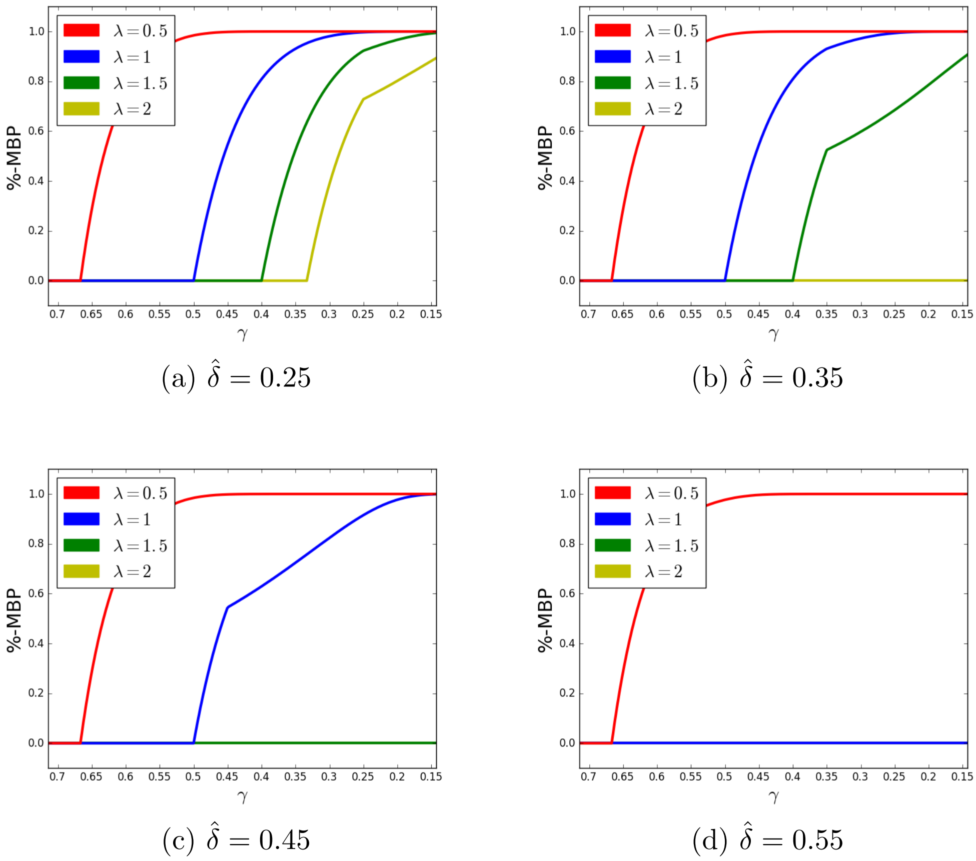
(iii) satisfies $\lim_{z \to \infty} k(z) = 0.$

[5] The conception and formulation of this proof has greatly benefited from extensive discussions with Bram Driesen.

(iv) is strictly decreasing in z.

Given these insights, it is possible to obtain the following result.

Proposition 2. *If the task-level shocks θ_1 and θ_2 are standard normally distributed, there exists a uniquely optimal degree of implementing management-by-exception for all possible firms.*



(a) $\hat{\delta} = 0.25$ (b) $\hat{\delta} = 0.35$

(c) $\hat{\delta} = 0.45$ (d) $\hat{\delta} = 0.55$

Figure 3: Increasing firm rigidity, measured by the optimal share of activities managed by plan (see Equation (10)), with increasing overresponsiveness of the manager.

In order to develop intuition for the qualitative and quantitative behaviour of the model with respect to its underlying parameters, I conduct a short simulation exercise. Although a closed-form solution for z does not exist, the owner's optimal action can be solved for numerically with arbitrary precision. To further facilitate interpretation, I express the owner's optimal solution as the expected share of the firm's activities dealt with via *management-by-plan*, henceforth denoted $\%MBP(z^*)$:

$$\begin{aligned}\%MBP(z^*) &\equiv \Phi^{2-sided}_{\theta_1,\theta_2}(z^*) = \Phi^{2-sided}_{\theta_1}(z^*) \cdot \Phi^{2-sided}_{\theta_2}(z^*) \\ &= \int_{-z^*}^{z^*} \phi(\theta_1)\,\mathrm{d}\theta_1 \cdot \int_{-z^*}^{z^*} \phi(\theta_2)\,\mathrm{d}\theta_2 \end{aligned} \tag{10}$$

This formulation intuitively picks up on the notion that higher levels of z correspond to a more rigid organisation (see Definition 1). As z increases, the share of events dealt with via a static plan without regard to actual occurrences in the world also increases, whereas at $z = 0$ all management is done case-by-case.

Figure 3 illustrates the solutions of Equation (10) for some exemplary parametric settings. Echoing the findings from Proposition 1, for each λ there exists a double threshold with respect to $\hat{\delta}$ and γ above which *management-by-exception* will not be implemented. However, as soon this threshold is crossed, the firm's drive to implement the practice rises sharply. For example, for $\lambda = 1$ and the manager's bias with $\hat{\delta} = 0.45$ just below the required threshold the firm already executes around 80% of its activities by plan if one task is three times more important than the other, making the firm very rigid. Although the exact values elicited should be taken with care, they suggest that the investigated underlying factors may, in fact, shape organisational structures in an economically meaningful way.

6 Conclusion

Although *management-by-exception* is a well-established concept enjoying widespread use in practice in a large variety of fields, this paper is the first to lay out a mathematical framework in order study the technique with theoretical rigour. I derive two main conclusions. First, under relatively mild assumptions I obtain a simple, sufficient condition for when firms will adopt *management-by-exception*. Second, I show that there exists a uniquely optimal degree of implementing *management-by-exception* with respect to the underlying parameters if the state of the economy is standard normally distributed.

Testing the model's predictions is an obvious next step for future research (see Section 4 for a discussion). Theoretically, it may be interesting to see how a growing number of tasks, interpretable as a growing firm size would affect the adoption choice of *management-by-exception* as well as how these drivers would interact with the ones established in this paper. Further, it may be interesting whether other established psychological biases, such as overconfidence or confirmatory base, on the part of the manager could act as drivers in adopting *management-by-exception*.

Apart from the applications mentioned so far, the mechanism can more generally be understood as a device for efficient attention allocation by negotiating *top-down* and *bottom-up* drivers in guiding focus (see Wolfe et al. (2003)), especially if an intra-personal view on the model is adopted (see footnote 3). The model's framework may thus be utilised to provide further structure to the *tunnelling*-mechanism described in Mullainathan and Shafir (2013) or even consumers reacting to *extraordinary events* in Reis (2004).

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Appendix A Proofs

A.1 Proof of Lemma 1

(i) As all of z, $g(z)$ and $\int_0^{\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} z} g(\theta_1)\,\mathrm{d}\theta_1$ are continuous functions everywhere, by the Combination Theorem for Continuous Functions it holds that $k(z)$ is also continuous everywhere.

(ii) As $k(0) = \frac{0}{0}$ and both its numerator and denominator are differentiable everywhere, l'Hôspital's rule may be applied.

$$\lim_{z\to 0} k(z) = \lim_{z\to 0} \frac{\frac{\partial}{\partial z}\left[z \cdot g((\frac{\gamma}{\delta})^{\frac{1}{\lambda}} z)\right]}{\frac{\partial}{\partial z}\left[\int_0^{\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} z} g(\theta_1)\,\mathrm{d}\theta_1\right]} = \lim_{z\to 0} (\frac{\delta}{\gamma})^{\frac{1}{\lambda}} + z \cdot \frac{g'\left((\frac{\gamma}{\delta})^{\frac{1}{\lambda}} \cdot z\right)}{g\left((\frac{\gamma}{\delta})^{\frac{1}{\lambda}} \cdot z\right)} = \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}} \tag{11}$$

Because of Definition 4 it must hold that $\left(\frac{\delta}{\gamma}\right) \geq 1$. Since $\lambda > 0$, we must have that $\lim_{z\to 0} k(z) \geq 1$.

A.2 Proof of Lemma 2

Differentiating $f(z)$ with respect to z yields

$$f'(z) = \left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} \cdot g\left(\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} \cdot z\right) \cdot z^{\lambda}\left(\beta_1\left(\frac{\gamma}{\delta}\right) - \beta_2\right) - \beta_2 \lambda z^{\lambda-1} \cdot \int_0^{\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} z} g(\theta_1)\,\mathrm{d}\theta_1 \tag{12}$$

Then for $z > 0$ and $1 > \gamma > 0$, setting $f'(z) \geq 0$ and rearranging yields the desired condition.

A.3 Proof of Proposition 1

Recall that by Lemma 1 *(ii)* $\lim_{z\to 0} k(z) = \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}}$. When $z \to 0$ it then holds that $k(z) > \lambda \cdot \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}} \frac{\delta}{1-\delta}$ if and only if $1 > \lambda \cdot \frac{\delta}{1-\delta}$. Due to the parsimonious assumptions placed on $g(\,\cdot\,)$ so far, not much can be said about the behaviour of $k(z)$ as z increases. Assume, however, that at $\tilde{z}$ it holds that $k(\tilde{z}) = \lambda \cdot \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}} \frac{\delta}{1-\delta}$, where $\tilde{z}$ may be arbitrarily large. If then $1 > \lambda \cdot \frac{\delta}{1-\delta}$ holds with strict inequality and since by Lemma 1 *(i)* $k(z)$ is continuous, there must be a range $(0, \tilde{z})$ with some strictly positive length where it also holds that $k(z) > \lambda \cdot \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}} \frac{\delta}{1-\delta}$. By Lemma 2, this also implies that $f'(z) > 0$ for the entire range. Because $\frac{\partial E[\pi]}{\partial z}|_{z=0} = 0$, this further implies that $\frac{\partial E[\pi]}{\partial z} > 0$ for all $z \in (0, \tilde{z})$. In this case, starting from $z = 0$ the owner can then increase expected profits by increasing z up to $\tilde{z}$, rendering $z = 0$ a strictly dominated strategy for the owner. If, on the other hand, there should exist no $\tilde{z}$ such that $k(\tilde{z}) = \lambda \cdot \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}} \frac{\delta}{1-\delta}$ (still assuming that $1 > \lambda \cdot \frac{\delta}{1-\delta}$), then $k(z) > \lambda \cdot \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}} \frac{\delta}{1-\delta}$ for all z and all $z > 0$ are better than $z = 0$. Therefore, if $1 > \lambda \cdot \frac{\delta}{1-\delta}$ then not implementing management-by-exception to any degree by choosing $z = 0$ is a strictly dominated strategy.

A.4 Proof of Corollaries 1-4

Since, in this paper, the manager's behavioural bias is the sole driver for the owner's motivation to adopt *management-by-exception*, doing so can never be desirable when no such bias exists. It is easy to verify this. By Lemma 2, $f(z)$ and thus $\frac{\partial E[\pi]}{\partial z}$ decreases if and only if $k(z) < \lambda \cdot \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}} \frac{\delta}{1-\delta}$. If the manager's decision bias vanishes as $\widehat{\delta} \to 1$ (and thus $\delta \to 1$), the right-hand side goes to ∞ and the inequality must hold for all z. Coupled with the insight that $\frac{\partial E[\pi]}{\partial z}|_{z=0} = 0$, this implies that in this case $\frac{\partial E[\pi]}{\partial z} < 0$ for all z and that the owner can increase expected profits by decreasing z from all strictly positive levels.

The further comparative statics results can be directly gained from the dominance-condition in Proposition 1. Not implementing *management-by-exception* is a strictly dominated option if $\lambda \cdot \frac{\delta}{1-\delta} < 1$. Ceteris paribus, this condition is more likely to hold if either λ or δ decrease. Recall, however, that by Definition 4 δ is bounded from below by the maximum of the parameters $\widehat{\delta}$ and γ. Hence, for a decrease in one of the two parameters to affect the adoption choice, the other one must be sufficiently low.

A.5 Proof of Lemma 3

(i) See Proof of Lemma 1.

(ii) See Proof of Lemma 1.

(iii) To show the desired result, I determine the limits of the numerator and denominator of $k(z)$ individually. For the denominator, note that because of symmetry of $\phi(\,\cdot\,)$ coupled with the fact that $\phi(\,\cdot\,)$ is a density function, it must hold that $\int_0^{\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} z} \phi(\theta_i)\, \mathrm{d}\theta_i = \frac{1}{2} > 0$.

For the numerator, first note that it must hold that $\lim_{z\to\infty} \int_0^z \phi(\theta_i)\theta_i \,\mathrm{d}\theta_i < \infty$, since by symmetry of $\phi(\,\cdot\,)$ (Assumption 1 *(iii)*) we would otherwise also have that $\lim_{z\to-\infty} \int_z^0 \phi(\theta_i)\theta_i \,\mathrm{d}\theta_i = -\infty$. In that case, however, $E[\theta_i]$ would not exist, contradicting Assumption 1 *(i)*.

With this in mind, I will proof the desired result by contradiction, assuming that $\lim_{z\to\infty} k(z) = C > 0$ where C is some finite, strictly positive constant. Then for all $\varepsilon > 0$, there exists a positive number M such that for all $\theta_i > M$ it holds that $|\phi(\theta_i)\cdot\theta_i - C| < \varepsilon$. Therefore, for all $\theta_i > M$ it must also hold that $C - \varepsilon < \phi(\theta_i)\cdot\theta_i < C + \varepsilon$. However, then for all $\varepsilon < C$ we would also have that

$$\infty = \int_M^\infty C - \varepsilon \,\mathrm{d}\theta_i < \int_M^\infty \phi(\theta_i)\theta_i \,\mathrm{d}\theta_i < \int_0^\infty \phi(\theta_i)\theta_i \,\mathrm{d}\theta_i$$

which contradicts the initial finding. As C cannot be negative, I conclude that it must hold that $C = 0$.

Combining the two insights, I conclude that

$$\lim_{z\to\infty} k(z) = \frac{0}{\frac{1}{2}} = 0 \tag{13}$$

(iv) Define the function

$$l(z) := \left(\int_0^{\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} z} \phi(\theta_1)\,\mathrm{d}\theta_1\right) \cdot \left(1 - \left(\frac{\gamma}{\delta}\right)^{\frac{2}{\lambda}} \cdot z^2\right) - z \cdot \phi\left(\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} z\right) \cdot \left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} \tag{14}$$

Note that $l(0) = 0$ and $l'(z) = -2z \cdot \left(\frac{\gamma}{\delta}\right)^{\frac{2}{\lambda}} \cdot \left(\int_0^{\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} z} \phi(\theta_1)\,\mathrm{d}\theta_1\right) < 0$ for all $z > 0$. Hence, it must hold that $l(z) < 0$ for all $z > 0$.

Differentiating $k(z)$ with respect to z yields:

$$k'(z) = \frac{l(z)\phi\left(\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} z\right)}{\left(\int_0^{\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} z} g(\theta_1)\,\mathrm{d}\theta_1\right)^2} \tag{15}$$

Because $\phi\left(\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} z\right) > 0$, $\left(\int_0^{\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}} z} g(\theta_1)\,\mathrm{d}\theta_1\right)^2 > 0$ and $l(z) < 0$ for all $z > 0$, it holds that $k'(z) < 0$ for all $z > 0$.

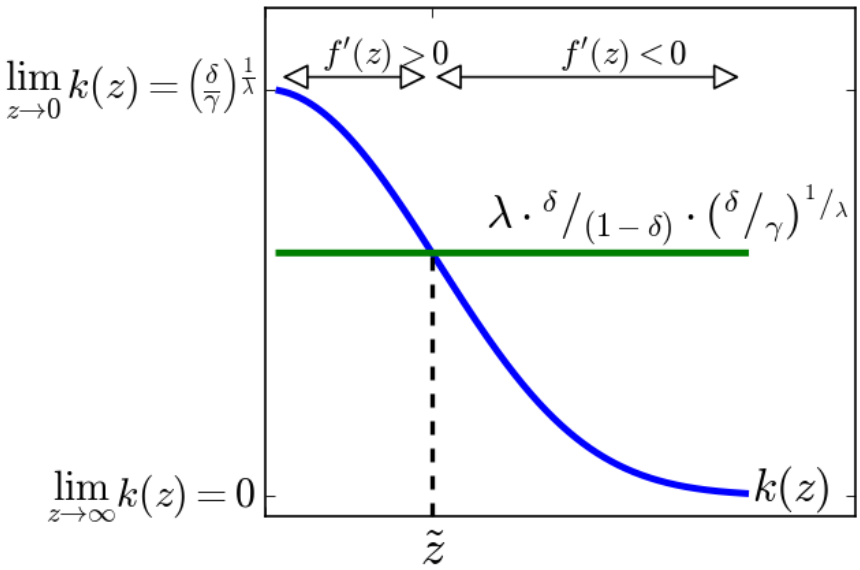

Figure 4: Illustration of findings from Lemma 2 and Lemma 3.

A.6 Proof of Proposition 2

The proof builds on the findings from Lemma 2 and Lemma 3, which are illustrated in Figure 4. It follows an intermediate-value-theorem-type of argument, relating $\lambda \cdot \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}} \frac{\delta}{1-\delta}$ and $k(z)$ (see Equation (7)). Since the former is a constant and the latter, by Lemma 3 *(i)* and *(iv)*, is continuous and strictly decreasing in z, there can either be no crossing or exactly one crossing between the two. I will discuss both possible cases in order.

As in Proposition 1, when $z \to 0$, by Lemma 3 *(ii)*, $k(z) < \lambda \cdot \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}} \frac{\delta}{1-\delta}$ if and only if $\lambda \cdot \frac{\delta}{1-\delta} > 1$. However, since by Lemma 3 *(iv)* $k(z)$ is strictly decreasing in z when θ_1 and θ_2 are drawn from a standard normal distribution, then this also implies that $k(z) < \lambda \cdot \left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}} \frac{\delta}{1-\delta}$ for all z. In turn, by Lemma 2 this implies that $f'(z) < 0$ for all z, which, coupled with the fact that $f(0) = 0$, implies that $f(z) < 0$ for all z. As characterising the sign of $f(z)$ is equivalent to characterising the slope of the expected profits, we know from this that $\frac{\partial E[\pi]}{\partial z} < 0$ for all z. Therefore, if $\lambda \cdot \frac{\delta}{1-\delta} > 1$ the owner can increase expected profits by decreasing z from all strictly positive levels. The uniquely optimal level for z is then at the its lowest possible level $z = 0$.

If, on the other hand, $\lambda\cdot\frac{\delta}{1-\delta} < 1$, then it holds that $\lim_{z\to 0} k(z) > \lambda\cdot\left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}}\frac{\delta}{1-\delta} > \lim_{z\to\infty} k(z)$ where the first inequality follows from Lemma 3 *(ii)* and the second from Lemma 3 *(iii)* (for all feasible parametric settings). Continuity of $k(z)$ (Lemma 3 *(i)*), by the intermediate value theorem, ensures that there is at least one crossing between $k(z)$ and $\lambda\cdot\left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}}\frac{\delta}{1-\delta}$ while the fact that $k(z)$ is strictly decreasing $k(z)$ (Lemma 3 *(iv)*) ensures that there is not more than one crossing. Denote $\tilde{z}$ where $k(\tilde{z}) = \lambda\cdot\left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}}\frac{\delta}{1-\delta}$. Thus, for all $z\in[0,\tilde{z})$ it holds that $k(z) > \lambda\cdot\left(\frac{\delta}{\gamma}\right)^{\frac{1}{\lambda}}\frac{\delta}{1-\delta}$ and by Lemma 2 that $f'(z) > 0$. Since furthermore $f(0) = 0$, it then holds that $f(z) > 0$ and thus that $\frac{\partial E[\pi]}{\partial z} > 0$ for all $z\in[0,\tilde{z})$. As in Proposition 1, the owner can strictly increase the firm's expected profits by increasing z at all $z\in[0,\tilde{z})$ whenever $\lambda\cdot\frac{\delta}{1-\delta} < 1$. However, because of the single-crossing property it now also holds that the slope of the expected profits decreases for all $z\in(\tilde{z},\infty)$.

In order to ensure that a maximum is reached for some z we now simply need to ensure that $f(z)$, and therefore the slope of the expected profits, does indeed turn negative at some point as z increases. This can be verified as follows.

$$\lim_{z\to\infty} f(z) = \beta_1 \lim_{z\to\infty}\int_0^{\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}}z}\phi(\theta_1)\theta_1^{\lambda}\,\mathrm{d}\theta_1 - \beta_2 \lim_{z\to\infty} z^{\lambda}\int_0^{\left(\frac{\gamma}{\delta}\right)^{\frac{1}{\lambda}}z}\phi(\theta_1)\,\mathrm{d}\theta_1 = -\infty \tag{16}$$

As noted in the proof for Lemma 3 *(iii)*, $\lim_{z\to\infty}\int_0^z \phi(\theta_1)\theta_1\,\mathrm{d}\theta_1$ converges to a finite constant. Since $0 < \delta,\gamma,\lambda < \infty$, so must the first addend. It is then easy to see that the second addend goes to $-\infty$, showing the desired result. Therefore, there must be some $z^* > \tilde{z}$ for which it holds that $\frac{\partial E[\pi]}{\partial z} > 0$ for all $z\in[0,z^*)$ and $\frac{\partial E[\pi]}{\partial z} < 0$ for all $z\in(z^*,\infty)$. Therefore, there also exists a unique level of z that maximises the firm's expected profits when $\lambda\cdot\frac{\delta}{1-\delta} < 1$, proving the desired result.