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Research Paper

FINANCIAL MATHEMATICS AND GAME THEORY APPLICATIONS

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INTRODUCTION

Over the past two decades, game theory has been applied to a growing variety of critical practical issues in economics, industrial organisation, corporate strategy, finance, accounting, market design, and marketing, such as antitrust analysis, monetary policy, and company restructuring. In this work, we discuss how game theory, especially the principal-agent model, is becoming more significant in the domains of finance and management accounting.

Mathematical models of conflict and cooperation between utility optimizers whose actions affect each other's utility are studied in game theory, and mathematical approaches for assessing such scenarios are provided. Thus, it is similar to operations research and, in particular, mathematical programming in terms of optimization [Shubik (2002)], which are normally concerned with a single optimizer. In order to examine and solve the mathematical models that it analyses, game theory employs theoretical notions such as Karush-Kuhn-Tucker optimality requirements, as well as numerical tools from mathematical programming. Parallel to

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mathematical programming, such models are idealised representations of an imagined reality, since many features of the actual world cannot be expressed mathematically. This kind of approximation has sparked a lot of philosophical debate [Gintis (2000)]. The notions of strategies, Nash equilibrium and its offspring, such as Bayesian equilibrium, as well as game theory's vocabulary for studying information sets have made it possible to codify scenarios of conflict and cooperation that emerge in a number of domains under the same roof. Thus, game theory [Aumann (1985), Fudenberg and Tirole (1991)], which began as an elegant mathematical discipline [von Neumann and Morgenstern (1944), Owen (1982), Forgó et al. (1999)], has been applied to an ever increasing number of important practical problems [Tirole (1986), Milgrom and Roberts (1992), Shubik (2002)] in economics [Friedman (1990), Gibbons (1992), Besanko et

Belief formation

Explaining financial crises through some self-prophesying behavior may appear to have some superstitious connotation. It is as if economic players have psychic powers to simply induce an outcome according to their will. By merely invoking their beliefs, they soon are able to steer the economy to some realities that vindicate their original beliefs, making it difficult for these events to have rational justification.

However, when one talks about rational players in any economic setting, one can at least say that the beliefs they have entertained in making decisions are never unfounded. Beliefs are more than just gut feelings or mood swings. As Savage would say in his classic book *Foundations of Statistics*, forming beliefs is a matter for calculation. If someone asks you whether you prefer Rs. 3^6 toRs. 5^4 , you might most probably say "Wait! I'll compute it first". Rational players would rather want to make their beliefs correct, if possible, and employ any available information or resources in making a good decision.

Now if everyone tries her best to make a good decision, how come they ended up in a crisis? Could an unfortunate event such as this well up from a group of rational individuals? There are three possible ways to resolve this. The first is to argue that some economic agents are in fact irrational or become irrational at some moment or circumstance. Not necessarily that they

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become crazy, but human nature is so complex that at times some value judgments in making choices become more meaningful than the rationality principle. This reasoning is so compelling that many of its adherents explain crisis through a number of behavioral models.

Complementarity of actions

When beliefs are formed and weighed, it is not immediate that people can already orient an economic outcome based on those beliefs. Unless they have hypnotic capacity to do so, their beliefs are meaningless without the actions that correspond to them. Actions thus are the ones that make those beliefs tangible in the economic world.

Moreover, a single action may not be sufficient to tip the economy towards one's liking. Oftentimes, a certain outcome is induced only when a critical mass of action of individuals is obtained. One can liken this to a group of protesters who could successfully create an insurgence once their number is enough to thrash the strength of the police force. In other words, there is an apparent correlation among the agents' actions that leads the economy towards a certain outcome. More specifically, there is complementarity between the collective actions of agents and the outcome these actions favor, i.e. it pays off to join a mutiny as long as it can topple the authority, otherwise it would be very dangerous to have the slightest thought of it. Or put in a more economic setting, depositors would only urgently withdraw their money from the bank if bankruptcy becomes imminent. But when is bankruptcy imminent? That is when everyone urgently withdraws from the bank! This sounds like an old circular argument but it is the process where self-fulfilling events can be well understood.

a) On sequential actions: Information cascades

Information cascades, which has found its application on financial crisis several years back (e.g. Welch, 1992), is related to the typical follow-the-leader phenom enon. Although it appears that the followers are merely following the footprints of the leader, it is basically the signals derived from the action of the leader that eventually makes others track the same action. An example of its mechanics is described as follows. Suppose there is a group of potential

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investors who are con templating to invest on a security in a sequential manner. If the first ones decide not to invest, those who will come after them will also choose not to invest even if they observe good signals or have good ex ante reasons to do otherwise. The rationale is that the news received by the first movers (whether correct or not) can simply overshadow the prior private information of the succeeding ones, influ encing them later to do the same action of not investing. This inefficiency arises especially when investors know that they only have a "rough"' idea about their own private information which can be easily affected by their predecessors' action. Banerjee (1992) extensively discussed this type of action and coined it *as* herd behavior. He showed that when people act based on the actions of others rather than on their own information, the resulting equilibrium is normally inefficient. Similar study was also conducted by Bikhchandani et. al. (1992) on this issue and was given some applications by Devenow and Welch (1996).

b) On simultaneous actions: Hierarchies of beliefs

The formation of beliefs is not *as* simple *as* its end-product action. Once an action is done, one can see that it is final and concrete. But the process of be lief formation from which an action is derived can be very rich and complicated. Rational individuals, for instance, in their effort to extract every possible infor mation at hand, are not only concerned about their beliefs about the economy but also about others' beliefs, and about others' beliefs on their beliefs about the economy, and so on. Thus, everyone engages oneself, whether with full or bounded rationality, into some hierarchies of beliefs before considering a particular action. They don't need to see the action of others to verify these beliefs, *as* in the case of cascades, they simply preempt others action to be such for fear of being trapped in a possible crisis.

CORPORATE FINANCE AND MANAGERIAL ACCOUNTING

The concept of von Neumann's anticipated utility [von Neumann and Morgenstern (1944)], on which fundamental conclusions on asset pricing and portfolio selection have been founded, was a major contribution of game theory to finance.

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When an investor's utility of consumption is quadratic and/or asset returns are multi-normally distributed, the capital asset pricing model (CAPM) uses a special case of this utility notion, in which investors are only concerned with the mean and variance of payoffs, to provide a theoretical basis for portfolio choice. Thus, it was shown that, in market equilibrium, diversification of holdings is optimum under such assumptions, and that the advantage achieved is dependent on the covariances of asset returns.

Markowitz's work on portfolio selection [Markowitz (1952), (1959), (2002), Farrar (1962), Philippatos (1973), Perold (1984), Elton and Gruber (1991), Zenios (1993), Rubinstein (2002)] incorporates the notion of the interactive effects of expected returns from a group of investments through the use of covariances, as well as the notion of diversification and selection of investment combinations, i.e., portfolios, that minimise risk He demonstrated that the certainty equivalent method's reasoning, namely a preference for predicted returns and aversion to risk, may lead to the creation of diversified portfolios. The method of certainty equivalence is based on the behavioural assumption that the investor has an expected utility function of the form 2 EU w [()] =, where w is a random variable representing the investor's wealth, and E[] = E[] = E[] = E[] = E[] = E[] = E[] = E[] = E[] = E[] = E[] = E[] = E[] = E[] = E[] = w is the anticipated value of an investor's wealth, w is its variance, and > 0 is the risk aversion coefficient. In this case, the investor compares the means and variances of the portfolios to which the asset would belong, rather than looking at each item individually. As a result, portfolios, not individual assets, determine the true range of investing options. As a result, the investor's purpose is to combine a collection of assets in such a way that the return is maximised for a given level of risk, or the risk is reduced for a given level of return. An efficient portfolio is a collection of assets or securities that meets this purpose. The investor makes portfolio choices based on the anticipated utility maximisation concept, and his behaviours follow rational behaviour guidelines. As a consequence, the MVM (mean variance portfolio selection model) is created:

Managerial Accounting

Principal-Agent Models and Incentive Contracting

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The role of compensation contracts in determining risk taking decisions in the financial industry is very important. Empirical evidence [Orphanidis (1996)] suggests that incentive compensation has substantial influence on risk decisions by money managers. Similar considerations have led to the introduction of agency models in order to analyze and design incentive contracting mechanisms.

Since the introduction of the principal-agent model by Mirlees (1976) and Holmström [Holmström (1979), (1982)], it has been used extensively in order to provide insight into incentive contracting and design of incentives and performance measures that alleviate moral hazard [Baiman Demski (1980), Baiman (1982), (1990), Baiman and Evans (1983), Murphy (1984), Kanodia (1985), Jewitt (1988), Jensen and Murphy (1990), Garen (1994), Baiman and Rajan (1995)], but also in order to provide insight into market failures that associate relationship specific assets and franchise contracts [Williamson (1971), (1979), (1983), Grossman and Hart (1986), Hart and Moore (1988), Minkler and Park (1994), Klein (1995), Wimmer and Garen (1997)]. It should be noted that these models differ from the evolutionary agent models used in agent-based computational economics, where economies are modeled as evolving decentralized systems of autonomous interacting agents in order to study the apparently spontaneous formation of global regularities in economic processes [LeBaron (1998), Tesfatsion (1998), (2001)].

The very basic principal-agent model is formulated for a principal and an agent involved in a contractual game. The agent faces a choice of accepting the principal's offer or declining it and seek employment elsewhere. The agent exerts an effort x that results in an output y observable by the risk neutral principal, who offers the agent a wage $w(y)$. The technology, which is common knowledge, is represented by the distribution function of output dependent on effort, i.e., $F(y \mid x)$. The risk-neutral principal observes output but not the agent's effort. It is assumed that $F(y \mid x)$ is absolutely continuous with respect to the same nonnegative measure for each x, thus, $F(\cdot)$ has a density f and

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$$F(y \mid x) = \int_{-\infty}^{y} f(t \mid x) d\sigma(t) \quad (6)$$

It is assumed that the agent has a separable vol Neumann-Morgenstern utility *u(w(y))-v(x)*, where *v*(·) is a private cost of effort for the agent. Since the agent is strictly risk and effort averse, *u*(·) is an increasing concave and *v*(·) is an increasing convex function. An optimal contract between the principal and the agent trades off risk sharing and incentives. In this setting, the agent is maximizing his income. The agent's reservation amount ρ denotes the expected utility he could receive in a different line of business, so the principal's choice of *w*(·) must be such that the agent's maximized utility must not be less than ρ . Thus, the principal's problem is then:

$$\max_{w,x} \int [y - w(y)] f(y \mid x) d\sigma(y) \quad (7)$$

s.t.

$$\int u(w(y)) f(y \mid x) d\sigma(y) - v(x) \geq \rho \quad (8)$$

$$x = \text{argmax} \int u(w(y)) f(y \mid t) d\sigma(y) - v(t) \quad (9)$$

The individual rationality or participation constraint (8) requires that the expected utility of the agent will be at least as much as its reservation price ρ . The incentive compatibility constraint (9) provides the agent with the motivation he needs to choose the effort level that the principal prefers, given the contract it is offered. Note that this is essentially a bi-level optimization problem [Migdalas et al. (1998)], where the second-level problem, the agent's utility maximization problem, is unconstrained. If the effort levels *x* are restricted to a set *X*, problem (1)-(1) turns explicitly into a constrained bi-level programming problem. In the absence of such constraints, the first-order approach [Mirrlees (1976), Holmström (1979), Milgrom (1981), Grossman and Hart (1983), Jewitt (1988)] replaces the incentive compatibility constraint with the condition that the agent's expected utility be stationary in effort, i.e.,

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$$\int u(w(y))f_x'(y \mid x)d\sigma(y) - v'(x) = 0 \qquad (10)$$

However, the two problems (7)-(9) and (7)-(8), (10) are not generally equivalent since not all stationary points are global maxima. On the other hand, if the agent's expected utility is concave in effort, the two problems have the same solution. Holmström (1979) showed that the necessary optimality conditions for problem (7)- (8), (10), the optimal compensation *w*(*y*) satisfies:

$$\frac{1}{u'(w(y))} = \lambda + \mu \frac{f_x'(y \mid x)}{f(y \mid x)}, \qquad (11)$$

where it has been established [Holmström (1979), Jewitt (1988)] that 0 ∝ > . Thus, the optimal compensation is such that the principal's expected payoff is strictly increasing in the agent's action. Equation (1) is related to the monotone likelihood ratio property (MLRP) which states that the compensation *w*(*y*) depends on the properties of the likelihood ratio $f_x{}'/f$ and implies, for instance, that *w*(*y*) is monotone increasing in *y*. This assumption is quite standard in the literature, and has fairly natural interpretations. It implies for instance that more effort means more output, and that the agent's payment increases with observed output [125]. However, the derivation of (1) requires the additional assumption that the distribution function of output in the agent's effort be convex at each level of output.

THRESHOLD BANK-RUN EQUILIBRIUM IN DYNAMIC GAMES

A widely recognized feature in cri sis models with self-fulfilling character is the presence of strategic complementarity. Agents tend to rationally cluster their actions towards a certain direction which eventually induces an economic outcome that it favors. In the case of bank-runs, this phenomenon is explained through the following argument: if depositors anticipate that others will run against the bank for fear of bankruptcy, their action in conforming to that belief provokes the bankruptcy itself. Consequently, when a sufficiently large number of individuals entertain such expectations, a bad outcome is soon realized. For many of

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these studies on crisis , this complementarity provides a quite compelling explanation on why large fluctuations suddenly occur in the economy. Models with multiple equilibria then becomes a natural norm in explaining that a crisis is nothing but a shift to a lower equilibrium point of the economy.

While economic "shifts" are normally attributed to some factors that typically explain the volatility in financial markets such as *irrational exuberance* and *animal spirits,* their influence remains to be regarded as exogenous from the formal the ory. Attempts to provide a more integrated model have recently made use of the tools on coordination games, particularly on the so-called global games framework introduced by Carlsson and van Damme (1993) [18] • In this approach, an equilib rium is seen as a cut-off point between crisis and no-crisis events, rather than a point of convergence to any change in agents' beliefs. This, in turn, achieves a uniqueness result which resolves the selection problem inherent in models with multiple equilibria.

However, one of the most important critiques in the application of global games to crisis events like bank-runs is its confinement to static structures. Agents main tain only a one-time discernment to either "run" or "remain" and the use of up dated information gathered over time, which could reinforce one's incentive to withdraw, is never taken into account. Whereas, when crisis is regarded as a dynamic event, agents acquire that option to withdraw at any stage if the pay off for doing so becomes higher than the expected returns from remaining, *i.e.* when bank-run becomes really imminent in that stage. Moreover, apart from the private information that one obtains through time, the fact that a bank has not failed in the past is a good signal that either it is strong or that there was really no potent belief among the other agents to abandon it. Thus, this type of learning through-time which is crucial in an environment with strategic uncertainty is not incorporated in the static model.

In this study, we address this need of extending the static bank-run model into a dynamic form. We take off from the model analyzed by Goldstein and Pauzner (2005) and show that bank-run threshold is a function of interest rates. Then, we set this model on a dynamic global games framework studied by Angeletos *et. al.* (2007), using monotone perfect Bayesian-Nash as

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a solution concept. We establish here how a simple recursive setup can generate a unique equilibrium strategy. Consequently, comparative statics is studied to show how the probability of bank run is affected over time by the inflow of private information and the knowledge that the bank has survived from the bad speculations in the past. Finally, we will also show that when an unobservable shock is introduced, multiplicity of equilibria can result in this dynamic learning process.

Monotone perfect Bayesian-Nash equilibrium

To characterize an equilibrium, recall that an agent chooses an action that maximizes her expected payoff difference between withdrawing and waiting, such that she chooses to withdraw (s_{it} = 0) if the expected payoff from withdrawing is higher, otherwise she chooses to wait (s_{it} = 1). As in the static model, the expected payoff difference depends mainly on the measure of agents who would want to withdraw which is implied by the level of fundamentals. Thus, we let conditional on the knowledge of one's own past and present signals and that bank-run has not yet occurred in the past as represented by agents' strategy St_{1} . Note that this characterization does not necessarily require an infinite horizon setting and is valid even with only a finite length of time *T*. Thus, we define our equilibrium concept as follows: The above definition is a perfect Bayesian-Nash equilibrium since at every subgame, every player chooses the optimal payoff given her own signal and the knowledge that bank-run has not occurred in the past. The fact that the bank continues to exist makes agent's actions sequentially rational as they do not depend on any other period. Moreover, any "off-the-equilibrium" action of any agent is negligible since apart from being unobservable, it forms part only of the final and summarized information that bank-run has not occurred in the past[21] . Therefore, an agent's expected payoff for waiting is determined only by Baye's rule at any relevant history of the game.

For t= 1, we have $\hat{x}_{i1} = xil$ and $\hat{s}_0 = 1$ *i.e.* trivially, no bank-run has occurred before period 1. This dynamic game played only in period 1 is analog to the static model that admits a unique equilibrium characterized by the thresholds for X_{i1} and θ. The result of Proposition 1 therefore applies also for this case of dynamic game with $t = 1$. For $t \geq 2$, the equilibrium strategy $S_{it}(\cdot)$

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is conditioned by the profile of i's signals over time *($\hat{x}_{it}$)* and the knowledge whether bank-run has already happened before the present time ($\hat{s}_{t-1}$). Given a uniform distribution about θ and errors ε_{it} being independent of θ and serially uncorrelated across time, the simple average $\hat{x}_{it} = \theta + \bar{\varepsilon}_{it}$ is a sufficient statistic for the profile of signals, $\hat{x}_{it}$ where $\bar{\varepsilon}_{it} = \frac{1}{t}\sum_{r=1}^{t} \varepsilon_{it}$ Thus, we summarize i's history of private information into a single parameter at each time *t*. Where no confusion may arise, we simply denote $\hat{x}_{it}$ and $\bar{\varepsilon}_{it}$ in this symmetric game as $\bar{x}_t$ and $\bar{\varepsilon}_t$, respectively.

MONITORING, CONTROL AND AGGREGATION

Monitoring in a contractual game is concerned with the stochastic augmentation of an initially designed performance measure by additional information collected at a cost, for instance if the principal undertakes a costly investigation.

Baiman and Demski (1980) addressed, under CI between y_1 and y_2, the question whether the principal would be willing to pay a cost in order to collect the additional output y_2 when the signal y_1 has already been observed. Such investigations on behalf of the principal could be used as a carrot, when y_1 is high, or stick, when y_2 is low, in order to motivate the agent, given that the cost is not so large that it never pays to monitor. It was shown by Dye (1986) that, under MLRP and IC, the risk aversion of the agent decides whether monitoring is used as a carrot or a stick.

The case where the principal must pay a fixed fee c in order to observe a signal y_2 in addition to y_1 is modeled by extending the model (1)-(1). A principal can observe y_1 before deciding whether to pay for an investigation. In general, he may choose to randomly investigate conditionally on the observed output. He has to choose $w(y_1, y_2)$ and $w(y_1)$, and probability $p(y_1)$ conditional on observed output y_1. Thus, his problem becomes:

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$$\max\int\int\{[y_1 - w(y_1,y_2) - c]\,p(y_1) + [y_1 - w(y_1)][1 - p(y_1)]\}\,dF_1(y_1\,|\,x)\,dF_2(y_2\,|\,x)$$

$$\text{s.t.}$$

$$\int\int\{u(w(y_1,y_2))p(y_1) + [1 - p(y_1)]u(w(y_1))\}\,dF_1(y_1\,|\,x)\,dF_2(y_2\,|\,x) - v(x) \geq \rho$$

$$x = \arg\max\int\int\{u(w(y_1,y_2))p(y_1) + [1 - p(y_1)]u(w(y_1))\}\,dF_1(y_1\,|\,t)\,dF_2(y_2\,|\,t) - v(t)$$

This model is linear in $p(y_1)$ implying that the optimal monitoring is of "all-or nothing" nature. At each y_1, the principal either monitors with probability 1 or does not monitor.

Transfer Pricing, Budgeting and Audits

The key components of organizational architecture are the assignment of decision rights, the measurement of performance, and the reward system. Where decisions rights are placed in a firm's hierarchy determines the extend to which the firm is centralized or decentralized [Arya et al. (1998f)]. In decentralized organizations transfer of goods and services takes place between the different divisions. In such a process, the producing division records an intrafirm revenue, while the purchasing division registers an intrafirm cost. Such activities necessiate the need for planning and coordination. Accounting practices such as allocations, transfer pricing and budgeting are used to coordinate. Cost allocation coordinate activities by assigning the cost of one activity to others in proportion to some measure of use [Rajan (1992)]. Budgeting attempts to coordinate activities by assigning targets for costs, revenues, production, etc, to managers. Most large corporations pay considerable attention to design elaborate capital budgeting systems in order to provide for decentralized decision making that provides incentives for agents at various level of the organization to make optimal choices [Harris and Raviv (1998)]. Budgeting is an exante process with communication and negotiation between divisional managers and a central firm manager. The term transfer price refers to the amount of monetary units of the interdivisional exchange. This phenomenon of pricing intrafirm transactions is called transfer pricing. Divisional profits reflect transfer prices.

Kanodia (1993) examined coordination and budgeting within the framework of the principal-agent model under the assumption that the managers' participation constraints must be

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satisfied state by state, rather than in an ex ante sense. He found that the firm is best off if it splitts its operations so that the performance measure of any manager is unaffected by the performance of other managers, and that the optimal coordination mechanism is a budget based mechanism. In Melumad et al. (1992), for stochastic production costs and revenues, under the RP, it is examined whether deviations from budget are entirely controllable by divisional managers.

Vaysman (1986) demonstrated how coordination mechanisms can be framed as transfer price mechanism. Under RP, coordination mechanisms result in budgeting rather than transfer pricing. However, when communication is limited, transfer pricing is superior to budget coordination mechanisms. In Melumad et al. (1995) it is shown that with limits on communication between divisional managers and the central manager, delegation of decisions has the advantage of allowing decisions to be made based on richer information processed by divisional managers and thus of greater flexibility gains.

Kanodia and Mukherji (1994) analyze a two- and a three-period model in order to obtain insights into the dynamics of audit pricing. The models assume that there is a pool of auditors, with identical technologies, who compete for the audit business of a client firm, that there is a start up cost when the auditor performs a first time audit, that there is a cost when the client switches auditors, and that there is an operating cost of an audit per period. For the two-period model, where the client expects to be in business for two periods and its financial statements are required to be audited in each of the two periods, the equilibrium is found by backward induction. The result is that given the informational advantage of the incumbent auditor, the client must make a “take-it-or-leave-it” price offer to him. Kanodia and Mukherji found out that for the three-period model, given the constraint that clients can write contracts only one period at a time, the optimal audit mechanism cannot be characterized using the RP, i.e., the incentive constraints [Laffont and Tirole (1986)] are not satisfied. The mechanism investigated by Kanodia and Mukherji involves determination of audit price through Bertrand competition among auditors.

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Morgan and Stocken (1998) investigate the effect of the litigation risk following an audit report (audit risk) on audit pricing and auditor turnover. The informed incumbent and the uninformed competitors simulatneously submit sealed bids for the audit. The client accepts the lowest bid. For a two-period model, a perfect Bayesian equilibrium involving mixed strategies is derived for the bidding game by backward induction. Their results indicate that auditor turnover will be higher for high-risk clients than for low-risk ones, that the expected litigation costs of high-risk firms are subsidized by low-risk firms, and that, on average, auditors make losses on high-risk audits and compensate for this from excess profits on low-risk audits.

In Fagart and Sinclair-Desgagné (2002), the information systems induced by auditing policies in a principal-agent model with moral hazard is studied. They conclude that the design of optimal auditing policies involves not only the trade-off between risk sharing and incentives, but also an examination of the location of risk.

Conclusions

Game theory has significantly contributed to the normative rules for the selection of portfolios as well as to the design of measures in and analysis of incentive contracting phenomena. We have also seen that game theoretic models have helped in gaining insights into and explain many phenomena, previously considered as paradoxes or anomalies, in finance. However, quite a few phenomenon remain unexplained and further effort is required. There seems to be two directions of research developing; behavioral modeling that moves away from the assumption of rational behavior [Thaler (1999)], and richer game theoretic models that employ information cascades, higher order beliefs and heterogeneous prior beliefs [Allen and Morris (1998)]. Similarly, while the game theory approach to managerial accounting has been successful in taking care of incentive problems that arise from hidden information and in providing valuable insights, strong assumptions on complete contracting, unlimited and costless communication, costless decision making, etc, prohibit in most cases the practical implementation of the theoretical results. Future research should be directed towards deriving and studying models based on softening of these assumptions. Moreover, mathematical

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programming techniques from bi-level optimization should be of help in carefully analyzing and solving the resulting models.

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