

A Model for Robust Regulation of Financial Networks

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Abstract

We develop a model to study the problem of a social planner who seeks to regulate a financial network in which shocks propagate across firms while she is unsure about the underlying network structure. We derive her optimal policy as a function of investors' attitudes towards risk and ambiguity, firms' information sets, and invariant network characteristics. Our preliminary results highlight the importance of uncertainty and firms' information sets on the optimal policy intervention.

I Problem

Consider a network $\mathcal{G} = (V, E)$ consisting on a set of n nodes, $V = \{1, \dots, n\}$, and a set of m undirected edges $\{e_{ij}\} \in E$. Each node i represents one of the institutions identity, and each edge e_{ij} represents the *correlation* or contagion factor between two entities. Let $(\Omega, \mathcal{A}, \mathbb{P})$ be a probability space ...

Consider a two-stage model, where on the first stage there is a random shock happening on the nodes. Let ξ_i a Bernoulli random variable such that $\xi_i^0 \in \{0, 1\}$, $i = 1, \dots, n$ represents the *distress state* of node- i on the network. On the other hand, the second stage captures the behavior of the *shock's propagation* over the network. In order to define this, consider the stochastic process P modeling the probability of contagion of a node, given that one of its neighbor is distressed, i.e., if $\xi_j^1 \in \{0, 1\}$ represents the distress state of node j in the second stage, then

$$P_{ij} = \mathbb{P}\{\xi_j^1(\cdot) = 1 \mid \xi_i^0 = 1\} \quad e_{ij} \in E, \forall i, j \in V$$

The problem is now to minimize the total cost of the system under shocks on the network. For this, the regulator is set to solve the problem of minimizing an overall cost, consisting on implementation cost and contagion cost, by deciding an optimal capital requirement. Let x^0 be the decision policy, $x^0 \in [0, 1]^n$ such that x_i^0 represents the policy required at entity i , and $x^1(\cdot)$ be a decision policy regarding the second stage (not sure if needed or not). The optimization problem is given by

$$\begin{aligned} (\mathcal{P}) \quad & \min_{\{x^0, x^1(\cdot)\}} \quad \phi^0(x^0) + \mathbb{E}\{\phi^1(\cdot, x^0, x^1(\cdot))\} \\ & \text{such that} \quad f^0(x^1) \leq 0 \\ & \quad f^1(x^0, x^1(\omega), \omega) \leq 0, \omega - \text{a.s.} \\ & \quad x^0 \in [0, 1]^n, x^1 : \Omega \rightarrow \mathbb{R}^N \end{aligned}$$

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26 where ϕ^0 is the total cost of implementing a capital requirement policy, and ϕ^1 is the total cost of the second stage
 27 (probably related to the contagion cost). Here, the network constraints are included in the constraints $\{f^0, f^1\}$ and
 28 for a random realization ω and a given policy x^1 , the cost $\phi(\omega, x^0, x^1(\omega))$ should reflect the cost of the contagion on
 29 the system. For example, one can be interested in minimizing the expected cost of the contagion, but it is easy to
 30 incorporate a risk-measure for minimizing, for example, a measure like $C - Var$ of the tail of the distribution of
 31 distressed nodes.

32 2 Tue, Feb 20th

33 We explore a model with the following features

- 34 1. Consider a graph $G = (N, E)$, where each node represents a financial institution, and each edge reflects finan-
 35 cial transactions between two institutions.
- 36 2. Institution i faces a financial shock, represented as ε_i , which impacts its assets over liabilities ratio, defined as
 37 $r_i = \frac{A_i}{L_i}$, ¹. Additionally, we consider that a financial institution is under *distress* if its ratio is under a (given)
 38 threshold $\lambda \in (0, 1)$. Thus,

$$i \text{ under distress} \iff r_i(1 - \varepsilon_i) < \lambda$$

- 39 3. There is a central decision maker, focus on the stability of the system. We discussed the information that
 40 is available to this regulator, and propose a mechanism to oversee the overall stability within the financial
 41 network through a constraint over the ratio, given by x_i .
- 42 4. The financial institutions decide their ratio by maximizing their profits², given by a function π_i , with the
 43 minimum level of A/L ratio, i.e.,

$$r_i(x_i; p) \in \operatorname{argmax}_r \{E^p\{\pi(r)\} \mid r \geq x_i, r \in R_i\}$$

44 Additionally, assuming that the function π_i is nonincreasing on r (and no further restrictions are imposed),
 45 the individual solution to this problem is given by $r_i^* = x_i$, i.e., the financial institution sets its ratio at mini-
 46 mum possible level.

- 47 5. There is contagion on the network, described in its stationary state as follows: if institution i gets distressed,
 48 there is a probability p that it affects its immediate neighbor, p^2 by a 2-edge neighbors, and so on. Defining
 49 the set $\{j \rightarrow i\}$ as the set of all possible simple paths coming to node i , and $d(j, i)$ the distance between j and i
 50 (amount of edges between them), the expected shock [Julio: Assuming that there is no amplification of shocks](#)
 51 is given by

$$\varepsilon_i = \sum_{j \rightarrow i} p^{d(i,j)} \varepsilon_j$$

52 and by defining the matrix $\mathcal{A}_{ij} = \sum_{j \rightarrow i} p^{d(i,j)}$, the acceptable shocks are the solution of the eigen problem for
 53 the matrix \mathcal{A} . Moreover, we interpret \mathcal{A} as an stochastic (transition) matrix by enlarging it with an extra *not*

¹Capital?

²utility?

54

distressed node as follows,

$$\tilde{\mathcal{A}} = \left[\begin{array}{c|ccccc|c} & 1 & 2 & \dots & n & ND \\ \hline 1 & 0 & \sum_{2 \rightarrow 1} p^{d(2,1)} & \dots & \sum_{n \rightarrow 1} p^{d(n,1)} & 1 - \sum \mathcal{A}_{1\cdot} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ n & \sum_{n \rightarrow 1} p^{d(n,1)} & \vdots & \dots & 0 & 1 - \sum \mathcal{A}_{1\cdot} \\ \hline ND & 0 & 0 & 0 & 0 & 1 \end{array} \right]$$

55 This is a stochastic matrix, and thus, it has an eigenvalue with value 1, which associated eigenvector $\tilde{\varepsilon}^0$. Let's
56 consider the first n components as acceptable shocks ε^0 for the corresponding nodes.

- Finally, consider the optimization problem solved by the central planner: set the ratio level [Julio: sth about the condition previously stated](#), such that it minimizes the total amount of financial institutions under distress. Let $y_i \in \{0, 1\}$ a binary variable such that $y_i = 1$ if institution i is under distress or $y_i = 0$ otherwise, and let $M > 0$ large enough such that

$$\min_{x,y} \sum_{i=1}^n y_i + \varphi(x, y) \quad (1)$$

$$\text{such that } r_i(x_i)(1 - \varepsilon_i^0) - \lambda \leq M(1 - y_i), \quad i = 1, \dots, N \quad (2)$$

57 where φ is a cost function associated to the policy x and the institutions on distress. Note that this formulation
58 depends on p and the topology of the network through the selection of the ε^0 .

- The optimization problem 1 can have a robust formulation by considering an ambiguity set for the parameter p , thus

$$\min_{x,y} \sup_{p \in \mathcal{A}(p_0)} \sum_{i=1}^n y_i + \varphi(x, y) \quad (3)$$

$$\text{such that } r_i(x_i)(1 - \varepsilon_i^0) - \lambda \leq M(1 - y_i), \quad i = 1, \dots, N \quad (4)$$

59 • Finally, we are looking for a representative agent formulation of the benevolent social planner problem, such
60 that the solutions of both problems coincide. For example, one wild guess is to consider the formulation
61 proposed in [?] [Julio: Citation needed](#), where ambiguity is considered as a family of possible models for the
62 parameter p , along with a probability distribution over these models, α . Therefore, the central planner prob-
63 lem has the following form

$$\max_x \left\{ \mathbb{E}^p \left\{ \sum_i u_i(x_i) \right\} - \frac{\mu}{2} \text{Var}^p \left(\sum_i u_i(x_i) \right) - \frac{\vartheta}{2} \text{Var}_\alpha \mathbb{E} \left(\sum_i u_i(x_i) \right) \right\}$$

64 3 Wed, Feb 21st

65 Continuing the idea of a (benevolent) central planner, let's define the following modified utility functions for each
66 agents:

$$\tilde{\pi}_i = \begin{cases} \pi_i & \text{institution } i \text{ operates normally} \\ 0 & \text{institution is on distress} \end{cases}$$

67 Therefore, we expect that the Central Planner solves the following problem

$$\max_x \left\{ \mathbb{E}^p \left\{ \sum_i \tilde{\pi}_i(x_i) \right\} - \frac{\mu}{2} \text{Var}^p \left(\sum_i \tilde{\pi}_i(x_i) \right) - \frac{\vartheta}{2} \text{Var}_{\alpha} \mathbb{E} \left(\sum_i \tilde{\pi}_i(x_i) \right) \right\}$$

68 Additionally, we modify the assumptions over the spread of the distress condition

69 3.1 Assumption (initial shocks) *Initial shock only affects one institution (node)*

70 3.2 Assumption (propagation) *Propagation occurs over simple paths*

71 Under Assumptions (3.1,3.2), one can formulate the probability of distress of node k , $\mathbb{P}\{D_k\}$, by a simple recursion. If j and i are directly connected, the probability is given by

$$\begin{aligned} \mathbb{P}_{j|i} &= \mathbb{P}\{D_j|D_i\} \\ &= \mathbb{P}\{r_j(1 - \varepsilon_j) < \lambda|D_i\} \\ &= \mathbb{P}\{r_j(1 - p\varepsilon_i) < \lambda|D_i\} \\ &= 1 - F_{\varepsilon_i} \left(\frac{1}{p} \left(1 - \frac{\lambda}{r_j} \right) \right) \end{aligned}$$

73 where F_{ε_i} corresponds to the cdf of ε_i . Finally, for every institution (node) of the network, the contagion will depend
74 only on all the possible simple paths connecting the corresponding node and the initially infested [Julio: ?](#). Therefore,

$$\mathbb{P}\{D_k\} = \sum_{l \rightarrow k} \mathbb{P}\{D_k|D_l\} \cdot \mathbb{P}\{D_l\} \quad (5)$$

75 3.1 Revisiting the institutions' problem

76 Let's consider an stochastic problem, where each node i faces uncertainty on the final ratio. Denote as ε the random
77 shock that the agent expects ($\mathbb{E}\varepsilon = \bar{\varepsilon} > 0$), and assume that every agent is risk neutral [Julio: focused on network
78 effects](#) and their profits are homogeneous and linear: $\pi(r) = a^0 - a^1 r$, $a^0, a^1 > 0$. Thus, the agent maximization
79 problem is given by

$$r_i(x_i; \bar{\varepsilon}) \in \underset{r}{\operatorname{argmax}} \left\{ \mathbb{E}\{\pi(r(1 - \varepsilon))\} \mid r \geq x_i, r \in R_i \right\}$$

80 Additionally, we include explicitly the participation constraint, where agent- i only participates in the economy
81 if its expected profits are nonnegative.

$$r_i(x_i; \bar{\varepsilon}) \in \underset{r}{\operatorname{argmax}} \left\{ a^0 - a^1(1 - \bar{\varepsilon})r \mid r \geq x_i, r \in R_i, a^0 - a^1(1 - \bar{\varepsilon})r \geq 0 \right\}$$

82 Note that in this formulation we consider agents that proceed in a *naïve* fashion by only maximizing their profits,
83 without considering its exposure within the network.

84 Following steps: Solve the problem considering

85 1. Risk neutral CP

86 2. Risk averse and Ambiguity neutral

87 3. Risk averse and Ambiguity averse

88 4. Numerical example

89 4 Toy Model

90 4.I Parameters

91 α^0

92 α^1

93 λ

94 F_ε

95 5 Thu, Feb 22

96 We realize that the only important condition for distress is given by the interaction of each node with its immediate
 97 neighbors. Consider the institution n , and denote by $N(n)$ the set of its neighbors, i.e., nodes that directly connect
 98 to n , and let q_n be the probability that institution n faces an idiosyncratic shock. Therefore, the probability of n
 99 entering the distress condition, D_n , is given by

$$\mathbb{P}\{D_n\} = q_n p_n^0 + \sum_{m \in N(n)} \mathbb{P}\{D_n | D_m\} \mathbb{P}\{D_m\},$$

100 where the first component of the sum reflects the distress due to a idiosyncratic shock to the institution n , and the
 101 associated probability of entering distress, $p_n^0 = \mathbb{P}\{r_n(1 - \varepsilon) < \lambda\}$, and the second component is the network effect,
 102 i.e., the probability of the contagion through the connection to the network.

103 Using matrix notation, define the matrix $\Gamma_{ij} = \mathbb{P}\{D_i | D_j\}$ for each $(i, j) \in E$, and zero otherwise. Then, the
 104 probabilities of distress are the solution of the system

$$P = qp^0 + \Gamma P \quad \Rightarrow \quad P = (I - \Gamma)^{-1}(qp^0) \quad (6)$$

105 Additionally, this equation imposes implicitly conditions over the parameters of the problems such that the solution
 106 is a vector of probabilities. We need to focus our attention to set of parameters such that the matrix Γ satisfies
 107 the following condition

$$(I - \Gamma)^{-1}(qp^0) \in [0, 1]^N$$

108 6 Optimal value of profits

109 For the CP problem, the expected utility is given by

$$\mathbb{E}\{\tilde{\pi}_i^*(x_i)\} = \mathbb{E}\mathbb{E}\{\tilde{\pi}_i^*(x_i) | D_i\}$$

110 7 Fri, Feb 23rd

$$r_i(x_i; F_\varepsilon(p, N)) \in \operatorname{argmax}_r \left\{ \mathbb{E}\{\pi(r(1 - \varepsilon))\} \mid r \geq x_i, \mathbb{E}\{\pi(r(1 - \varepsilon))\} \geq 0 \right\}$$

111 7.1 Analyzing the shock

112 The shock have two possible sources: Idiosyncratic ε^I , and Non-Idiosyncratic (coming from the network), ε^{Nt} . For
 113 insititution i , the probability of receiving the idiosyncratic shock is given by q_i , and we assume that $\varepsilon_i^I \sim U[0, UB]$,
 114 and that

$$\varepsilon = \begin{cases} \varepsilon^I & \mathbb{P}\{\cdot\} = q_i \\ \varepsilon^{Nt} & 1 - q_i \end{cases}$$

115 We realize that the contagion mechanism and the shock propagation are going to be analyzed with different
 116 perspective

- 117 • The idiosyncratic risk can be initiated at node i with probability q_i
- 118 • Once the institution i receives the shock, it propagates it with an intensity of p times the shock **Julio: note that**
 119 **here, we can consider $p < 1$ for mitigation effect, or $p > 1$ for an increasing effect.**
- 120 • The shock only propagates by simple paths between nodes (no revisiting allowed)

121 7.1 Assumption (shock propagation) *The shock always propagates, independently of the distress condition of*
 122 *the institution.*

- 123 • The final form for the shock faced by each institution is given by the equation

$$\varepsilon = \left(\sum_{n=1}^{|N|-1} p^n A^n + I \right) q \varepsilon^I \quad (7)$$

124 **Julio: Check the information available for each agent: Is the node totally visible for each agent?** We will continue
 125 assuming perfect information wrt the network

126 7.2 i -maximization problem

Define the *modified agent maximization problem*

$$\begin{aligned} & \max_r \mathbb{E}\{\pi(r(1 - \varepsilon))\} \\ & \text{such that } r \geq x, \\ & \mathbb{E}\{\pi(r(1 - \varepsilon))\} \geq 0, \end{aligned}$$

127 where ε comes from Equation (7). Note that by the linearity of the propagation, ε^3 followed the distribution of ε^I ,
 128 modified by a constant (easy to compute). Thus, define these coefficients as S_i ⁴, and let's compute the expectation,

$$\pi(\tau) = \begin{cases} a^0 - a^1 \tau & \tau \geq \lambda \\ 0 & \text{o.w.} \end{cases}$$

³Simple paths?

⁴ $S = (\sum p^n A^n + I)q$

129

$$\begin{aligned}
E\{\pi(r(1-\varepsilon))\} &= E\left\{ E\{\pi(r(1-\varepsilon))|r(1-\varepsilon) \geq \lambda\} + E\{\pi(r(1-\varepsilon))|r(1-\varepsilon) < \lambda\} \right\} \\
&= \left(\int_{\{\varepsilon: r(1-\varepsilon) \geq \lambda\}} (\alpha^0 - \alpha^1 r(1-\tau)) P(d\tau) \right) P\{r(1-\varepsilon) \geq \lambda\} \\
&= \begin{cases} 0 & 1 - \frac{\lambda}{r} \leq 0 \\ \alpha^0 - \alpha^1 r(1 - E\{\varepsilon\}) & \frac{1}{S \cdot UB} (1 - \frac{\lambda}{r}) \geq 1 \\ (1 - \frac{\lambda}{r}) \int_0^{1-\frac{\lambda}{r}} (\alpha^0 - \alpha^1 r(1-t)) \frac{dt}{S \cdot UB} & \text{o.w.} \end{cases} \\
&= \begin{cases} 0 & 1 - \frac{\lambda}{r} \leq 0 \\ \alpha^0 - \alpha^1 r(1 - E\{\varepsilon\}) & \frac{1}{S \cdot UB} (1 - \frac{\lambda}{r}) \geq 1 \\ \frac{1}{S^2 \cdot UB^2} (1 - \frac{\lambda}{r})^2 (\alpha^0 - \alpha^1 \frac{r+\lambda}{2}) & \text{o.w.} \end{cases}
\end{aligned}$$

130 8 Wed, Feb 28th

131 The computation of the expectation is

$$E\{\pi(r(1-\varepsilon))\} = \begin{cases} 0 & 1 - \frac{\lambda}{r} \leq 0 \\ \alpha^0 - \alpha^1 r(1 - E\{\varepsilon\}) & \frac{1}{S \cdot UB} (1 - \frac{\lambda}{r}) \geq 1 \\ \frac{1}{(S \cdot UB)^2} (1 - \frac{\lambda}{r})^2 (\alpha^0 - \alpha^1 r(1 - \frac{1}{2}(1 - \frac{\lambda}{r})) & \text{o.w.} \end{cases}$$

132 Note that this function is continuous. The optimal value for $x \geq 0$ is given by

$$r^*(x) \in \underset{r}{\operatorname{argmax}} \left\{ E\{\pi(r(1-\varepsilon))\} \mid r \geq x, E\{\pi(r(1-\varepsilon))\} \geq 0 \right\} = \begin{cases} \emptyset & x \geq \frac{\alpha^0}{\alpha^1} \frac{1}{1 - E\{\varepsilon\}} \\ \frac{\lambda}{1 - S \cdot UB} & 0 \leq x < \frac{\lambda}{1 - S \cdot UB} \\ x & \text{o.w.} \end{cases} \quad (8)$$

133 The function $E\{\pi(r(1-\varepsilon))\}$ is depicted in Figure (1). From here it is easy to see that the optimum of the optimization
134 problem depends on the values of x .

135 Finally, the optimal expected utility is given by

$$E\pi\{r^*(x)(1-\varepsilon)\} = \begin{cases} \alpha^0 - \alpha^1 x (1 - E\{\varepsilon\}) & \frac{\lambda}{1 - S \cdot UB} \leq x \leq \frac{\alpha^0}{\alpha^1} \frac{1}{1 - E\{\varepsilon\}} \\ \alpha^0 - \alpha^1 \frac{\lambda}{1 - S \cdot UB} (1 - E\{\varepsilon\}) & 0 \leq x \leq \frac{\lambda}{1 - S \cdot UB} \\ 0 & \text{o.w.} \end{cases} \quad (9)$$

136 and it's depicted on Figure (2).

137 9 Thu, Mar 1st

138 9.I CP Problem

139 Assuming a risk-averse central planner, we can compute the individual variance by considering different cases

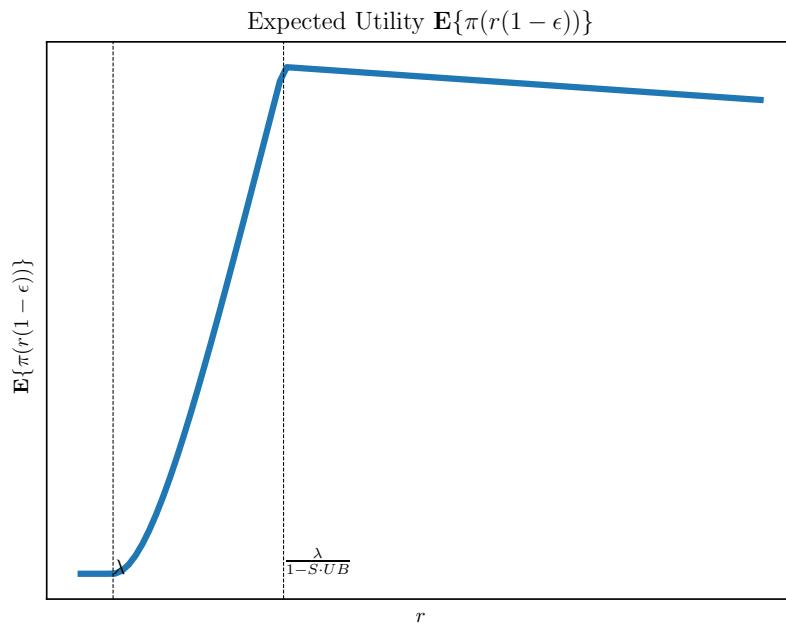


Figure 1: Expected utility

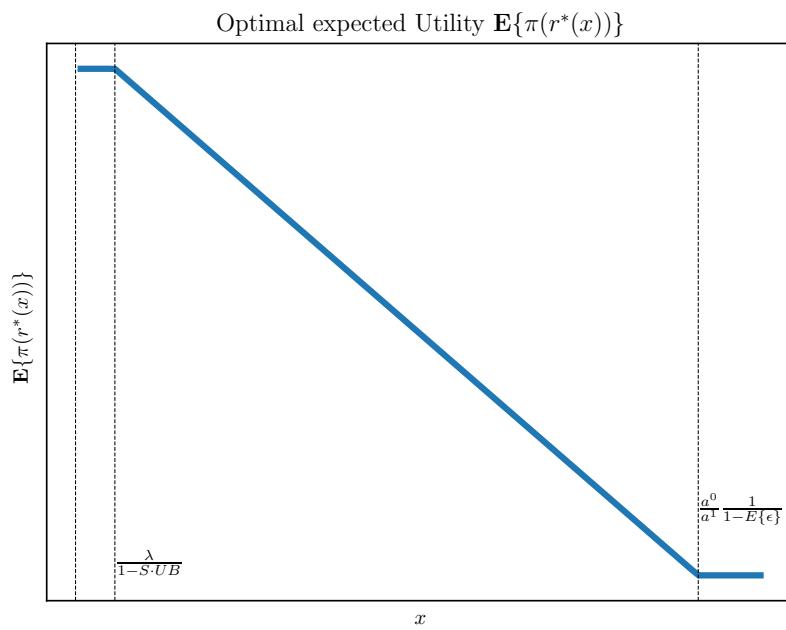


Figure 2: Optimal Expected utility

¹⁴⁰ $x_i \in (0, \lambda_i = \frac{\lambda}{1-S_i \cdot UB})$ In this case, the optimal rule corresponds to $r_i^*(x_i) = \lambda_i$ and the final expression of the vari-
¹⁴¹ ance does not depend on x . Nevertheless, it is given by

$$\text{var}\{\pi_i(r_i^*(x_i)(1 - \varepsilon_i))\} = \begin{cases} (\alpha_1 \lambda_i)^2 \frac{(S_i \cdot UB)^2}{12} & 1 - \frac{\lambda}{\lambda_i} > S_i \cdot UB \\ 0 & 1 - \frac{\lambda}{\lambda_i} < 0 \\ \left(1 - \frac{\lambda}{\lambda_i}\right) (\alpha_1 \lambda_i)^2 \int_0^{1-\frac{\lambda}{\lambda_i}} (\tau - E\varepsilon)^2 P(d\tau) & \text{o.w.} \end{cases}$$

¹⁴² $x_i \in (\lambda_i, \frac{\alpha_1^0}{\alpha_1} \frac{1}{1-E\varepsilon})$ Here, $r_i^*(x_i) = x_i$

$$\text{var}\{\pi_i(r_i^*(x_i)(1 - \varepsilon_i))\} = \begin{cases} (\alpha_1 x)^2 \frac{(S_i \cdot UB)^2}{12} & x \geq \lambda_i \\ \left(1 - \frac{\lambda}{x}\right)^2 \frac{(\alpha_1 x)^2}{3S_i \cdot UB} \left(\left(1 - \frac{\lambda}{x} - \frac{S_i \cdot UB}{2}\right)^2 - \frac{S_i \cdot UB}{2} \left(1 - \frac{\lambda}{x} - \frac{S_i \cdot UB}{2}\right) + \left(\frac{S_i \cdot UB}{2}\right)^2 \right) & \text{o.w.} \end{cases}$$

¹⁴³ Julio: check the regions!

¹⁴⁴ 9.2 Individual Variances

¹⁴⁵ The individual variance is given by

$$\text{var}\{\pi_i(r_i^*(x_i)(1 - \varepsilon_i))\} = \begin{cases} (\alpha_1 \lambda_i)^2 \frac{(S_i \cdot UB)^2}{12} & \lambda \leq x \leq \lambda_i \\ (\alpha_1 x)^2 \frac{(S_i \cdot UB)^2}{12} & \lambda_i \leq x \leq 1 \\ 0 & \text{o.w.} \end{cases} \quad (10)$$

¹⁴⁶ 9.3 Pairwise Covariances

¹⁴⁷ Consider the nodes i and j . The covariance of the profits between these two institutions can be decompesed according
¹⁴⁸ to the values of x_i and x_j . It's easier to see this on the Figure (3).

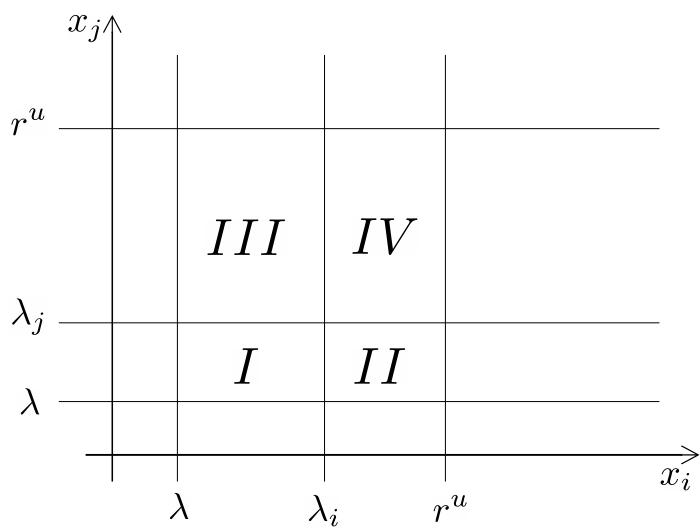


Figure 3: Areas for Covariances

149 After some algebra, the final form of the covariances is given by

$$\text{cov}(\pi_i(r_i^*(x_i(1 - \varepsilon_i))), \pi_j(r_j^*(x_j(1 - \varepsilon_j)))) = \begin{cases} (\alpha_1)^2 S_i S_j \lambda_i \lambda_j \frac{(UB)^2}{12} & \lambda \leq x_i \leq \lambda_i, \lambda \leq x_j \leq \lambda_j, (I) \\ (\alpha_1)^2 S_i S_j x_i \lambda_j \frac{(UB)^2}{12} & \lambda_i \leq x_i \leq r^u, \lambda \leq x_j \leq \lambda_j, (I) \\ (\alpha_1)^2 S_i S_j \lambda_i x_j \frac{(UB)^2}{12} & \lambda \leq x_i \leq \lambda, \lambda_j \leq x_j \leq r^u, (III) \\ (\alpha_1)^2 S_i S_j x_i x_j \frac{(UB)^2}{12} & \lambda_i \leq x_i \leq r^u \lambda, \lambda_j \leq x_j \leq r^u, (IV) \\ 0 & \text{ow} \end{cases} \quad (II)$$

150 **Julio: Note** By definition of the matrix S , it can be interpreted as the truncation of an exponential matrix

$$S = \left(\sum_{n=1}^{N-1} (pA)^n + I \right) q = \left(\sum_{n=0}^{N-1} (pA)^n \right) q \approx e^{pA} q,$$

151 although if we rule out cycles, technically, the matrix does not have elements on the diagonal, thus, it is not A

152 9.4 Risk-neutral Central Planner

153 Recall the following definitions

$$S = \sum_{n=0}^{N-1} (pA)^n q, \quad \varepsilon^I \sim U(0, UB), \quad \lambda_i = \frac{\lambda}{1 - S_i \cdot UB}, \quad r^u = \frac{\alpha^0}{\alpha^1} \frac{1}{1 - E\varepsilon}$$

154 The risk-neutral CP maximizes the following function

$$\begin{aligned} f(x) &= E \left\{ \sum_{i=1}^N \pi_i(r_i^*(x_i)(1 - \varepsilon_i)) \right\} \\ &= \sum_{i=1}^N E \left\{ \pi_i(r_i^*(x_i)(1 - \varepsilon_i)) \right\} \\ &= \sum_{i=1}^N \begin{cases} \alpha^0 - \alpha^1 \lambda_i (1 - E\{\varepsilon\}) & 0 \leq x_i \leq \lambda_i \\ \alpha^0 - \alpha^1 x_i (1 - E\{\varepsilon\}) & \lambda_i \leq x_i \leq r^u \\ 0 & \text{ow} \end{cases} \end{aligned} \quad (12)$$

155 Here, we have two cases: the CP is allowed to impose individual constraints x_i , or a general rule $x_i = x, \forall i$. The
156 solution to these problems:

157 Individual policy In this case, the problem of maximizing the function $f(x)$ defined in Equation (12) is separable,
158 and the solution is given by

$$\max_{(x_1, \dots, x_N)} f(x) \iff x_i^* \in \operatorname{argmax} E\pi_i(r_i^*(x_i)(1 - \varepsilon_i)) = [0, \lambda_i], i = 1, \dots, N \quad (13)$$

159 Global policy In this case, the CP is only able to choose one value of x for every node of the network. Therefore,
160 the solution that maximizes the utility is given by

$$\max_x f(x) \iff x^* \in \operatorname{argmax} \sum_i E\pi_i(r_i^*(x)(1 - \varepsilon_i)) = [0, \min_{i=1, \dots, N} \{\lambda_i\}] \quad (14)$$

161 **Julio: Note** that this analysis always incorporates that the agents internalize the non-default condition, i.e., if the
162 policy x is too low, they natural move their optimal level to the one that avoid the default case

163 9.5 Risk-averse CP

164 Given a parameter of risk aversion ϑ , the CP solves the following problem

$$x^* \in \operatorname{argmax}_x \left\{ \mathbb{E} \left(\sum_i \pi_i(r_i^*(x_i)(1 - \varepsilon_i)) \right) - \frac{\vartheta}{2} \operatorname{var} \left(\sum_i \pi_i(r_i^*(x_i)(1 - \varepsilon_i)) \right) \right\}$$

165 and the formula for the variance can be obtained using Equations (10,11), and it is given by

$$\operatorname{var} \left(\sum_i \pi_i(r_i^*(x_i)(1 - \varepsilon_i)) \right) = \sum_i \operatorname{var}(\pi_i(r_i^*(x_i)(1 - \varepsilon_i))) + 2 \sum_{j < i} \operatorname{cov}(\pi_i(r_i^*(x_i)(1 - \varepsilon_i)), \pi_j(r_j^*(x_j)(1 - \varepsilon_j)))$$

166 IO Mon, Mar 5th

167 10.1 Toy example

168 Consider the following economy,

$$N = \{0, 1, 2\}, \quad E = \{(0, 1), (1, 2)\}, \quad \lambda = 5\%, \quad UB = \frac{1}{4}, \quad p = \frac{1}{2}, \quad a_0 = a_1 = 1, \quad q_0 = q_1 = q_2 = \frac{1}{3},$$

169 this easy example is depicted in Figure (4) For this economy, we first compute

$$\begin{aligned} \mathbb{E}\varepsilon &= \frac{1}{8}, \\ S_0 = S_2 &= \frac{1}{n} \{1 + p + p^2\} \\ &= \frac{7}{12} \\ S_1 &= \frac{1}{n} \{p + 1 + p\} \\ &= \frac{2}{3} \\ \lambda_0 = \lambda_2 &= \frac{\lambda}{1 - S_0 \cdot UB} \\ &= \frac{12}{205} \approx 5.85\% \\ \lambda_1 &= \frac{\lambda}{1 - S_1 \cdot UB} \\ &= \frac{6}{100} = 6\% \\ r^u &= \frac{a_0}{a_1} \frac{1}{1 - \mathbb{E}\varepsilon} \\ &= \frac{8}{7} \end{aligned}$$

170 and we have the following features:

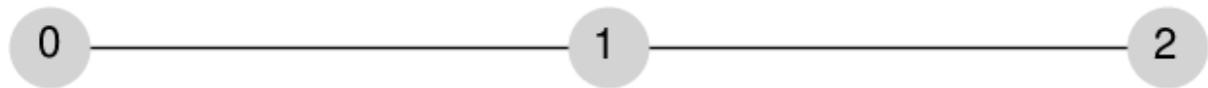


Figure 4: Toy example

171 Expected utility Using Equation (??), we have

$$\begin{aligned} \mathbb{E}\pi_0\{r_0^*(x)(1-\varepsilon)\} = \mathbb{E}\pi_2\{r_2^*(x)(1-\varepsilon)\} &= \begin{cases} \frac{389}{410} & 0 \leq x \leq \frac{12}{205} \\ 1 - \frac{7}{8}x & \frac{12}{205} \leq x \leq \frac{8}{7} \end{cases} \\ \mathbb{E}\pi_1\{r_1^*(x)(1-\varepsilon)\} &= \begin{cases} \frac{379}{400} & 0 \leq x \leq \frac{6}{100} \\ 1 - \frac{7}{8}x & \frac{6}{100} \leq x \leq \frac{8}{7} \end{cases} \end{aligned}$$

172 Variances Using Equation (??), we have

$$\begin{aligned} \text{var}\pi_0\{r_0^*(x)(1-\varepsilon)\} = \text{var}\pi_2\{r_2^*(x)(1-\varepsilon)\} &= \begin{cases} \frac{1}{12} \left(\frac{12}{205}\right)^2 \frac{49}{48^2} & 0 \leq x \leq \frac{12}{205} \\ \frac{1}{12} x^2 \frac{49}{48^2} & \frac{12}{205} \leq x \leq 1 \end{cases} \\ \text{var}\pi_1\{r_1^*(x)(1-\varepsilon)\} &= \begin{cases} \frac{1}{12} \left(\frac{6}{100}\right)^2 \frac{1}{36} & 0 \leq x \leq \frac{6}{100} \\ \frac{1}{12} x^2 \frac{1}{36} & \frac{6}{100} \leq x \leq 1 \end{cases} \end{aligned}$$

173 Covariances Using Equation (??) we have

$$\begin{aligned} \text{cov}(\pi_0(x_0), \pi_2(x_2)) &= \begin{cases} \left(\frac{7}{12}\right)^2 \left(\frac{12}{205}\right)^2 \frac{1}{12 \cdot 16} & 0 \leq x_0 \leq \frac{12}{205}, 0 \leq x_1 \leq \frac{12}{205} \\ \left(\frac{7}{12}\right)^2 \frac{12}{205} \frac{1}{12 \cdot 16} x_0 & \frac{12}{205} \leq x_0 \leq 1, 0 \leq x_1 \leq \frac{12}{205} \\ \left(\frac{7}{12}\right)^2 \frac{12}{205} \frac{1}{12 \cdot 16} x_2 & 0 \leq x_0 \leq 1, \frac{12}{205} \leq x_1 \leq \frac{12}{205} \\ \left(\frac{7}{12}\right)^2 \frac{1}{12 \cdot 16} x_0 x_2 & \frac{12}{205} \leq x_0 \leq 1, \frac{12}{205} \leq x_1 \leq 1 \end{cases} \\ \text{cov}(\pi_0(x_0), \pi_1(x_1)) &= \begin{cases} \frac{7}{3 \cdot 205 \cdot 100 \cdot 16} & 0 \leq x_0 \leq \frac{12}{205}, 0 \leq x_1 \leq \frac{6}{100} \\ \frac{7}{3 \cdot 100 \cdot 12 \cdot 16} x_0 & \frac{12}{205} \leq x_0 \leq 1, 0 \leq x_1 \leq \frac{6}{100} \\ \frac{7}{6 \cdot 3 \cdot 205 \cdot 16} x_1 & 0 \leq x_0 \leq 1, \frac{6}{100} \leq x_1 \leq \frac{6}{100} \\ \frac{7}{6 \cdot 3 \cdot 12 \cdot 16} x_0 x_1 & \frac{12}{205} \leq x_0 \leq 1, \frac{6}{100} \leq x_1 \leq 1 \end{cases} \end{aligned}$$

174 II Thu, Mar 8th

175 II.I Computing the ambiguity term

176 In this subsection we're interested in computing the term corresponding to the ambiguity of the CP. Recall that
 177 we introduce ambiguity on the rate of the shock contagion, p , where now we consider that it can have different
 178 values, p_0, \dots, p_K with associated probabilities $\alpha_k = \mathbb{P}\{p = p_k\}$, and such that $\mathbb{E}\{p\} = p_0$. Thus, we compute the
 179 following term

$$\text{var}_\alpha \left(\sum_i \mathbb{E}^p \pi_i(x_i) \right) = \sum_i \text{var}_\alpha \mathbb{E}^p \pi_i(x_i) + \sum_{j < i} \text{cov}(\mathbb{E}^p \pi_i(x_i), \mathbb{E}^p \pi_j(x_j))$$

180 Let's compute those terms individually:

181 Individual variance The individual variance produce by the ambiguity is given by

$$\begin{aligned} \text{var}_\alpha \mathbb{E}^p \pi_i(x_i) &= \alpha_1^2 \sum_k \alpha_k (\max\{x_i, \lambda_i(p_k)\}(1 - S_i(p_k)\mathbb{E}\varepsilon) - \max\{x_i, \lambda_i(p_0)\}(1 - S_i(p_0)\mathbb{E}\varepsilon))^2 \\ &= \alpha_1^2 \sum_k \alpha_k (\max\{x_i(1 - S_i(p_k)\mathbb{E}\varepsilon), \lambda\} - \max\{x_i(1 - S_i(p_0)\mathbb{E}\varepsilon), \lambda\})^2 \end{aligned}$$

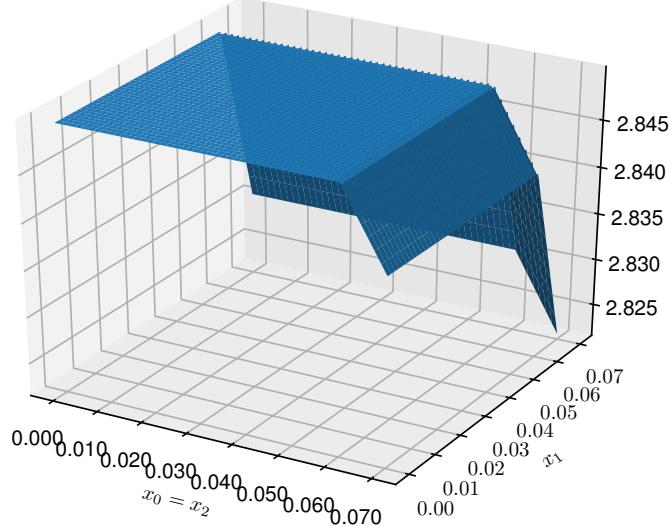
¹⁸² Covariances Following the same strategy, the covariances are given by

$$\begin{aligned}\text{cov}_\alpha(\mathbb{E}^p \pi_i(x_i), \mathbb{E}^p \pi_j(x_j)) &= \alpha_1^2 \sum_k \alpha_k (\max\{x_i, \lambda_i(p_k)\}(1 - S_i(p_k)\mathbb{E}\varepsilon) - \max\{x_i, \lambda_i(p_0)\}(1 - S_i(p_0)\mathbb{E}\varepsilon)) \\ &\quad \cdot (\max\{x_j, \lambda_j(p_k)\}(1 - S_j(p_k)\mathbb{E}\varepsilon) - \max\{x_j, \lambda_j(p_0)\}(1 - S_j(p_0)\mathbb{E}\varepsilon)) \\ &= \alpha_1^2 \sum_k \alpha_k (\max\{x_i(1 - S_i(p_k)\mathbb{E}\varepsilon), \lambda\} - \max\{x_i(1 - S_i(p_0)\mathbb{E}\varepsilon), \lambda\}) \\ &\quad \cdot (\max\{x_j(1 - S_j(p_k)\mathbb{E}\varepsilon), \lambda\} - \max\{x_j(1 - S_j(p_0)\mathbb{E}\varepsilon), \lambda\})\end{aligned}$$

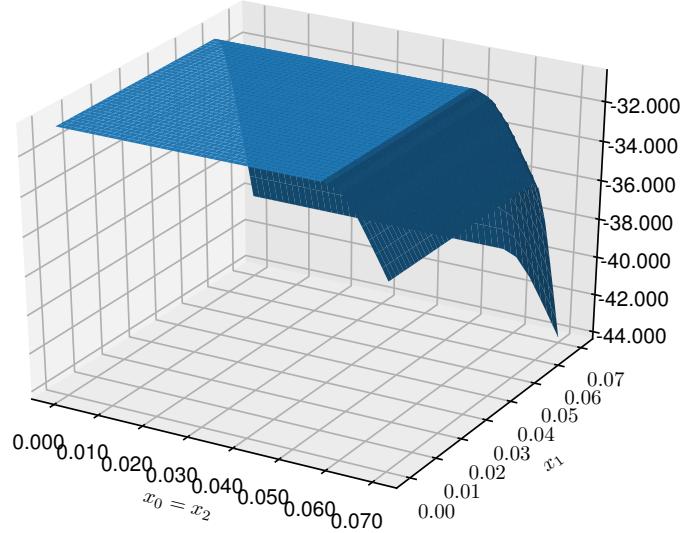
¹⁸³ I2 Fri, Mar 9th

¹⁸⁴ I2.I Plots

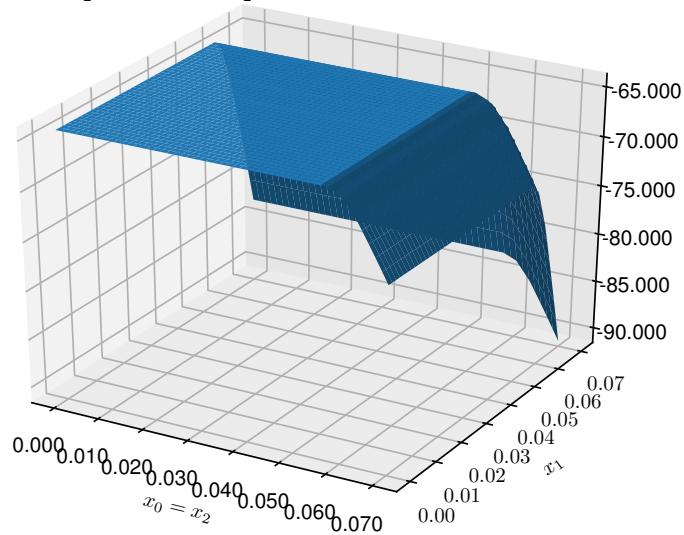
$$\mathbb{E}\{\sum_i \pi_i^*\} - \frac{\theta}{2}\text{var}(\sum_i \pi_i^*) - \frac{\gamma}{2}\text{var}_\alpha(E \sum_i \pi_i^*), \theta = 0.000, \gamma = 0.000$$



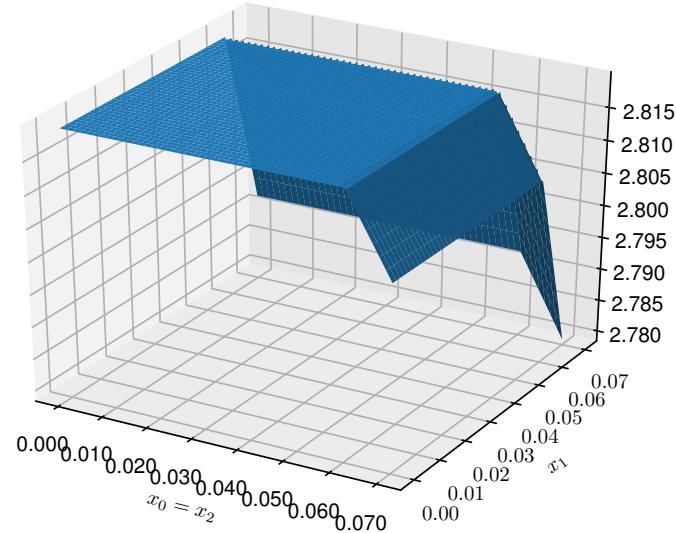
$$\mathbf{E}\{\sum_i \pi_i^*\} - \frac{\theta}{2}\text{var}(\sum_i \pi_i^*) - \frac{\gamma}{2}\text{var}_\alpha(E \sum_i \pi_i^*), \theta = 0.000, \gamma = 1000.000$$



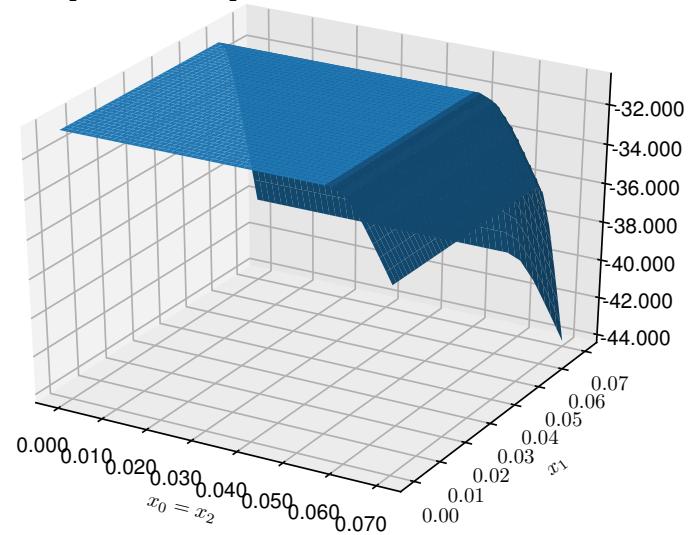
$$\mathbf{E}\{\sum_i \pi_i^*\} - \frac{\theta}{2}\text{var}(\sum_i \pi_i^*) - \frac{\gamma}{2}\text{var}_\alpha(E \sum_i \pi_i^*), \theta = 0.000, \gamma = 2000.000$$



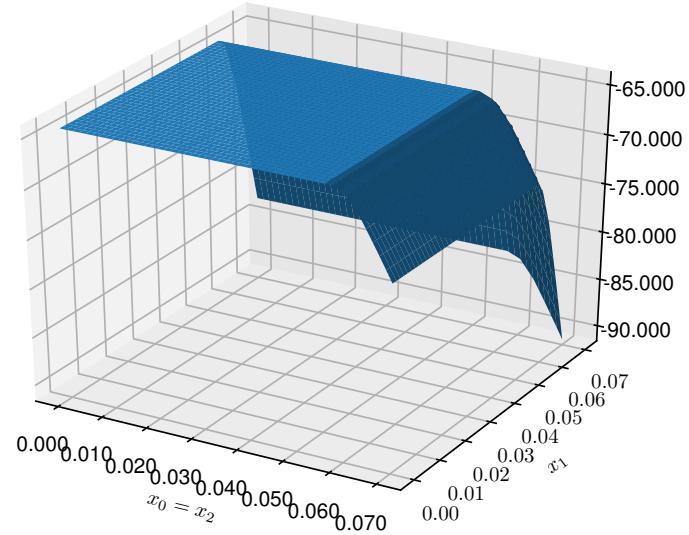
$$\mathbf{E}\{\sum_i \pi_i^*\} - \frac{\theta}{2}\text{var}(\sum_i \pi_i^*) - \frac{\gamma}{2}\text{var}_\alpha(E \sum_i \pi_i^*), \theta = 1000.000, \gamma = 0.000$$



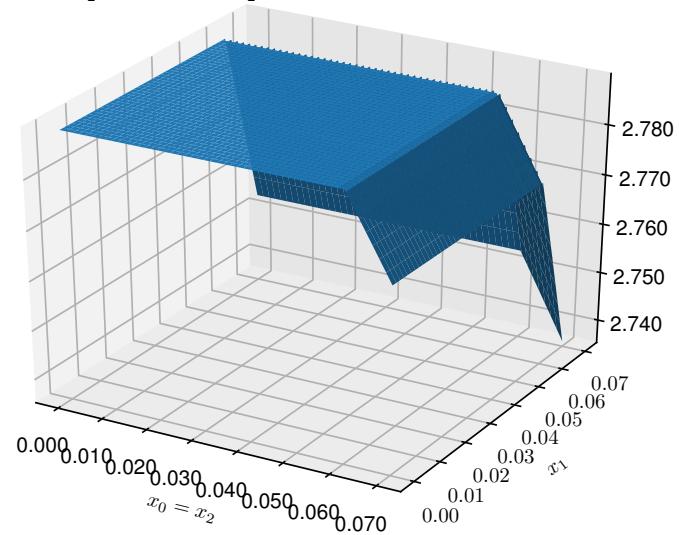
$$\mathbf{E}\{\sum_i \pi_i^*\} - \frac{\theta}{2}\text{var}(\sum_i \pi_i^*) - \frac{\gamma}{2}\text{var}_\alpha(E \sum_i \pi_i^*), \theta = 1000.000, \gamma = 1000.000$$



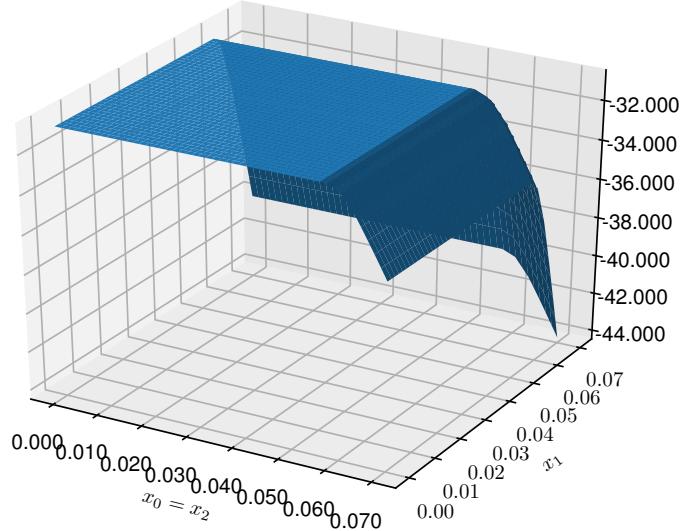
$$\mathbf{E}\{\sum_i \pi_i^*\} - \frac{\theta}{2}\text{var}(\sum_i \pi_i^*) - \frac{\gamma}{2}\text{var}_\alpha(E \sum_i \pi_i^*), \theta = 1000.000, \gamma = 2000.000$$



$$\mathbf{E}\{\sum_i \pi_i^*\} - \frac{\theta}{2}\text{var}(\sum_i \pi_i^*) - \frac{\gamma}{2}\text{var}_\alpha(E \sum_i \pi_i^*), \theta = 2000.000, \gamma = 0.000$$



$$\mathbf{E}\{\sum_i \pi_i^*\} - \frac{\theta}{2}\text{var}(\sum_i \pi_i^*) - \frac{\gamma}{2}\text{var}_\alpha(E \sum_i \pi_i^*), \theta = 2000.000, \gamma = 1000.000$$



$$\mathbf{E}\{\sum_i \pi_i^*\} - \frac{\theta}{2}\text{var}(\sum_i \pi_i^*) - \frac{\gamma}{2}\text{var}_\alpha(E \sum_i \pi_i^*), \theta = 2000.000, \gamma = 2000.000$$

