Cost Functions and Model Combination for VaR-Based Asset Allocation Using Neural Networks

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***Abstract*—We introduce an asset-allocation framework based on the active control of the value-at-risk of the portfolio. Within this framework, we compare two paradigms for making the allocation using neural networks. The first one uses the network to make a *forecast* of asset behavior, in conjunction with a traditional mean-variance allocator for constructing the portfolio. The second paradigm uses the network to *directly make the portfolio allocation decisions*. We consider a method for performing soft input variable selection, and show its considerable utility. We use model combination (committee) methods to systematize the choice of hyperparemeters during training. We show that committees using both paradigms are significantly outperforming the benchmark market performance.**

***Index Terms*—Asset allocation, financial performance criterion, model combination, recurrent multilayer neural networks, value-at-risk.**

I. Introduction

In finance applications, the idea of training learning algorithms according to the criterion of interest (such as profit) rather than a generic prediction criterion, has gained interest in recent years. In asset-allocation tasks, this has been applied to training neural networks to directly maximize a Sharpe Ratio or other risk-adjusted profit measures [1]–[3].

One such risk measure that has recently received considerable attention is the value-at-risk (VaR) of the portfolio, which determines the maximum amount (usually measured in, e.g., $) that the portfolio can lose over a certain period, with a given probability.

Although the VaR has been mostly used to estimate the risk incurred by a portfolio [4], it can also be used to actively control the asset allocation task. Recent applications of the VaR have focused on extending the classical Markowitz mean-variance allocation framework into a mean-VaR version; that is, to find an efficient set of portfolios such that, for a given VaR level, the expected portfolio return is maximized [5], [6].

In this paper, we investigate training a neural network according to a learning criterion that seeks to maximize profit under a VaR constraint, while taking into account transaction costs. One can view this process as enabling the network to directly learn the mean-VaR efficient frontier, and use it for making asset allocation decisions; we call this approach the decision model. We compare this model to a more traditional one (which we call the forecasting model), that uses a neural network to first make a forecast of asset returns, followed by a classical mean-variance portfolio selection and VaR constraint application.

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II. Value at Risk

A. Assets and Portfolios

In this paper, we consider only the discrete-time scenario, where one period (e.g., a week) elapses between times $t-1$ and t, for $t \geq 0$ an integer. By convention, the tth period is between times $t-1$ and t.

We consider a set of N assets that constitute the basis of our portfolios. Let $\mathbf{R}_t$ be the random vector of simple asset returns obtained between times $t-1$ and t. We shall denote a specific realization of the returns process—each time made clear according to context—by $\{\mathbf{r}_t\}$.

Definition 1: A portfolio $\mathbf{x}_t$ defined with respect to a set of N assets is the vector of amounts invested in each asset at a time t given

$$\mathbf{x}_t = (x_{1t}, x_{2t}, \cdots, x_{Nt})' \tag{1}$$

where $x_{it} \in \mathbb{R}$ and $-\infty < x_{it} < \infty$.

(We use bold letters for vectors or matrices; the $'$ represents the transpose operation.)

The amounts x_{it} are chosen causally: they are a function of the information set available at time t, which we denote by $\mathcal{I}_t$. These amounts do not necessarily sum to one; they represent the net position (in, e.g., $) taken in each asset. Short positions (negative x_{it}) are allowed.

The total return of the portfolio $\mathbf{x}_{t-1}$ during the period t is given by $R_t = \mathbf{x}'_{t-1}\mathbf{R}_t$.

B. Defining Value at Risk

Definition 2: The VaR with probability α of the portfolio $\mathbf{x}_{t-1}$ over period t is the value $V_t \geq 0$ such that

$$\Pr[\mathbf{R}'_t\mathbf{x}_{t-1} < -V_t \,|\, \mathcal{I}_{t-1}] = 1 - \alpha. \tag{2}$$

The VaR of a portfolio can be viewed as the maximal loss that this portfolio can incur with a given probability α, for a given period of time. The VaR reduces the risk to a single figure: the maximum amount V_t that the portfolio can lose over one period, with probability α.

C. The Normal Approximation

The value at risk V_t of a portfolio $\mathbf{x}_{t-1}$ is not a quantity that we can generally measure, for its definition (2) assumes a com-

plete knowledge of the conditional distribution of returns over period t. To enable calculations of the VaR, we have to rely on a model of the conditional distribution; the model that we consider is to approximate the conditional distribution of returns by a normal distribution. We qualify this normality assumption at the end of this section.

1) One-Asset Portfolio: Let us for the moment consider a single asset, and assume that its return distribution over period t, conditional on $\mathcal{I}_{t-1}$, is

$$R_t \sim \mathcal{N}(\mu_t, \sigma_t^2), \qquad \sigma_t^2 > 0 \tag{3}$$

which is equivalent to

$$\Pr[R_t < r_t \,|\, \mathcal{I}_{t-1}] = \Phi\left(\frac{r_t - \mu_t}{\sigma_t}\right) \tag{4}$$

where $\Phi(\cdot)$ is the cumulative distribution function of the standardized normal distribution, and μ_t and σ_t^2 are, respectively, the mean and variance of the conditional return distribution.

According to this model, we compute the α-level VaR as follows: let x_{t-1} be the (fixed) position taken in the asset at time $t-1$. We choose $r_t = \sigma_t \Phi^{-1}(1-\alpha) + \mu_t$ that we substitute in the above equation, to obtain

$$\Pr[R_t < \sigma_t \Phi^{-1}(1-\alpha) + \mu_t \,|\, \mathcal{I}_{t-1}] = 1 - \alpha \tag{5}$$

whence

$$\Pr[R_t x_{t-1} < (\sigma_t \Phi^{-1}(1-\alpha) + \mu_t) x_{t-1} \,|\, \mathcal{I}_{t-1}] = 1 - \alpha \tag{6}$$

and, comparing (2) and (6),

$$\begin{aligned} V_t &= -(\sigma_t \Phi^{-1}(1-\alpha) + \mu_t) x_{t-1} \\ &= (\sigma_t \Phi^{-1}(\alpha) - \mu_t) x_{t-1} \end{aligned} \tag{7}$$

using the fact that $\Phi^{-1}(1-\alpha) = -\Phi^{-1}(\alpha)$ from the symmetry of the normal distribution.

2) Estimating V_t: Let $\hat{\mu}_t$ and $\hat{\sigma}_t$ be estimators of the parameters of the return distribution, computed using information $\mathcal{I}_{t-1}$. (We discuss below the choice of estimators.) An estimator of V_t is given by

$$\hat{V}_t = (\hat{\sigma}_t \Phi^{-1}(\alpha) - \hat{\mu}_t) x_{t-1}. \tag{8}$$

If $\hat{\mu}_t$ and $\hat{\sigma}_t$ are unbiased, $\hat{V}_t$ is also obviously unbiased.

3) N-Asset Portfolio: The previous model can be extended straightforwardly to the N-asset case. Let the conditional distribution of returns be

$$\mathbf{R}_t \sim \mathcal{N}(\boldsymbol{\mu}_t, \boldsymbol{\Gamma}_t) \tag{9}$$

where $\boldsymbol{\mu}_t$ is the vector of mean returns, and $\boldsymbol{\Gamma}_t$ is the covariance matrix of returns (which we assume is positive-definite). Let $\mathbf{x}_{t-1}$ the fixed positions taken in the assets at time $t-1$. We find the α-level VaR of the portfolio for period t to be

$$V_t = \Phi^{-1}(\alpha) \sqrt{\mathbf{x}_{t-1}' \boldsymbol{\Gamma}_t \mathbf{x}_{t-1}} - \boldsymbol{\mu}_t' \mathbf{x}_{t-1}. \tag{10}$$

In some circumstances (especially when we consider short-horizon stock returns), we can approximate the mean asset returns by zero. Letting $\boldsymbol{\mu}_t = \mathbf{0}$, we can simplify the above equation to

$$V_t = \Phi^{-1}(\alpha) \sqrt{\mathbf{x}_{t-1}' \boldsymbol{\Gamma}_t \mathbf{x}_{t-1}}. \tag{11}$$

We can estimate V_t in the N-asset case by subsituting estimators for the parameters in the above equations. First, for the general case

$$\hat{V}_t = \Phi^{-1}(\alpha) \sqrt{\mathbf{x}_{t-1}' \hat{\boldsymbol{\Gamma}}_t \mathbf{x}_{t-1}} - \hat{\boldsymbol{\mu}}_t' \mathbf{x}_{t-1} \tag{12}$$

and when the mean asset returns are zero,

$$\hat{V}_t = \Phi^{-1}(\alpha) \sqrt{\mathbf{x}_{t-1}' \hat{\boldsymbol{\Gamma}}_t \mathbf{x}_{t-1}}. \tag{13}$$

4) On the Normality Assumption: It is now established in the finance literature that the returns distribution for individual stocks over short horizons exhibit significant departures from normality [7] ("fat tails"). Furthermore, several types of derivative securities, including options, have sharply nonnormal returns.

However, for returns over longer horizons and for stock indexes (as opposed to individual stocks), the normality assumption can remain a valid one. Indeed, on our datasets (described in Section V), a Kolmogorov–Smirnov test of normality fails to reject the null hypothesis on neither the TSE 300 monthly returns ($p = 0.2$), nor on the returns of 13 (out of 14) individual subsectors (except one) making up the TSE 300 index, at the 95% level.

The asset return distribution can of course be estimated from empirical data, using kernel methods [8] or neural networks [9]. The remaining aspects of our methodology are not fundamentally affected by the density estimation method, even though further VaR analysis is made more complex when going beyond the normal approximation. The results that we present in this paper nevertheless rely on this approximation, since our datasets are fairly well explained by this distribution.

D. The VaR as an Investment Framework

The above discussion of the VaR took the "passive" viewpoint of estimating the VaR of an existing portfolio. We can also use the VaR in an alternative way to actively control the risk incurred by the portfolio. The asset-allocation framework that we introduce to this effect is as follows:

1) At each time-step t, a *target VaR* $\tilde{V}_{t+1}$ is set (for example by the portfolio manager). The goal of our strategy is to construct a portfolio $\mathbf{x}_t$ having this target VaR.

2) We consult a decision system, such as a neural network, to obtain *allocation recommendations* for the set of N assets. These recommendations take the form of a vector $\mathbf{y}_t$, which gives the *relative weightings* of the assets in the portfolio; we impose no constraint (e.g., positivity or sum-to-one) on the y_{it}.

3) The recommendation vector $\mathbf{y}_t$ is *rescaled* by a constant factor (see below) in order to produce a vector $\mathbf{x}_t$ of final positions (in dollars) to take in each asset at time t. This rescaling is performed such that the estimator $\hat{V}_{t+1|t}$ (computed given the information set $\mathcal{I}_t$)

of the portfolio VaR over period $t+1$ is equal to the target VaR, $\tilde{V}_{t+1}$.

4) Borrow the amount $\sum_{i=1}^{N} x_{it}$ at the risk-free rate r_{0t} and invest it at time t in the portfolio $\mathbf{x}_t$ for exactly one period. At the end of the period, evaluate the profit or loss (using a performance measure explained shortly.)

It should be noted that this framework differs from a conventional investment setting in that the profits generated during one period *are not reinvested* during the next. All that we are seeking to achieve is to construct, for each period, a portfolio $\mathbf{x}_t$ that matches a given target VaR $\tilde{V}_{t+1}$. We assume that it is always possible to borrow at the risk-free rate to carry out the investment.

We mention that a framework similar to this one is used by at least one major Canadian financial institution for parts of its short-term asset management.

E. Rescaling Equations

Our use of the VaR as an investment framework is based on the observation that a portfolio with a given target VaR $\tilde{V}_{t+1}$ can be constructed by homogeneously multiplying the recommendations vector $\mathbf{y}_t$ (which does not obey any VaR constraint) by a constant

$$\mathbf{x}_t = \beta_t \, \mathbf{y}_t \tag{14}$$

where $\beta_t \geq 0$ is a scalar. To simplify the calculation of β_t, we make the assumption that the asset returns over period $t+1$, follow a zero-mean normal distribution, conditional on $\mathcal{I}_t$

$$\mathbf{R}_{t+1} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Gamma}_{t+1}) \tag{15}$$

with $\boldsymbol{\Gamma}_{t+1}$ positive-definite. Then, given a (fixed) recommendations vector $\mathbf{y}_t$, $\|\mathbf{y}_t\| > 0$, the rescaling factor is given by

$$\beta_t = \frac{\tilde{V}_{t+1}}{\Phi^{-1}(\alpha)\sqrt{\mathbf{y}_t' \, \boldsymbol{\Gamma}_{t+1} \, \mathbf{y}_t}}. \tag{16}$$

It can be verified directly by substitution into (11) that the VaR of the portfolio $\mathbf{x}_t$ given by (14) is indeed the target VaR $\tilde{V}_{t+1}$.

1) Estimating β_t: In practice, we have to replace the $\boldsymbol{\Gamma}_{t+1}$ in the above equation by an estimator. We can estimate the rescaling factor simply as follows:

$$\hat{\beta}_t = \frac{\tilde{V}_{t+1}}{\Phi^{-1}(\alpha)\sqrt{\mathbf{y}_t' \, \hat{\boldsymbol{\Gamma}}_{t+1} \, \mathbf{y}_t}}. \tag{17}$$

Unfortunately, even if $\hat{\boldsymbol{\Gamma}}_{t+1}$ is unbiased, $\hat{\beta}_t$ is biased in finite samples (because, in general for a random variable $X > 0$, $\mathrm{E}[1/X] \neq 1/\mathrm{E}[X]$). However, the samples that we use are of sufficient size for the bias to be negligible. Reference [10] provides a proof that $\hat{\beta}_t$ is asymptotically unbiased, and proposes another (slightly more complicated) estimator that is unbiased in finite samples under certain assumptions.

F. The VaR as a Performance Measure

The VaR of a portfolio can also be used as the risk measure to evaluate the performance of a portfolio. The performance measure that we consider for a fixed strategy S is a simple average of the VaR-corrected net profit generated during each period (see, e.g., [4], for similar formulations)

$$W^S = \frac{1}{T} \sum_{t=1}^{T} W_t^S \tag{18}$$

where W_t^S is the (random) net profit produced by strategy S over period t (between times $t-1$ and t), computed as follows (we give the equation for W_{t+1} to simplify the notation):

$$W_{t+1}^S = (\mathbf{R}_{t+1} - \iota \, r_{0t})' \mathbf{x}_t^S + \mathsf{loss}_t. \tag{19}$$

This expression computes the excess return of the portfolio for the period (over the borrowing costs at the risk-free rate r_{0t}), and accounts for the transaction costs incurred for establishing the position $\mathbf{x}_t$ from $\mathbf{x}_{t-1}$, as described below. We note that the profit does not require a normalization by the risk measure, since the portfolio $\mathbf{x}_t^S$ is already risk-constrained.

1) Estimating W^S and W_t^S: To estimate the quantities W^S and W_t^S, we substitute for $\{\mathbf{R}_t\}$ the realized returns $\{\mathbf{r}_t\}$, and we use the target VaR $\tilde{V}_t$ as an estimator of the portfolio VaR V_t

$$\hat{W}^S = \frac{1}{T} \sum_{t=1}^{T} \hat{W}_t^S \tag{20}$$

$$\hat{W}_{t+1}^S = \frac{(\mathbf{r}_{t+1} - \iota \, r_{0t})' \mathbf{x}_t^S + \mathsf{loss}_t}{\tilde{V}_{t+1}}. \tag{21}$$

As for $\hat{\beta}_t$, we ignore the finite-sample bias of these estimators, for it is of little significance for the sample sizes that we use in practice.

Examining (20), it should be obvious that this performance measure is equivalent to the well-known Sharpe ratio [11] for symmetric return distributions (within a multiplicative factor), with the exception that it uses the *ex ante* volatility (VaR) rather than the *ex post* volatility as the risk measure.

2) Transaction Costs: Transaction costs are modeled by a simple multiplicative loss

$$\mathsf{loss}_t = -\mathbf{c}' \, |\mathbf{x}_t - \tilde{\mathbf{x}}_t| \tag{22}$$

where $\mathbf{c} = (c_1, \cdots, c_N)'$, c_i the relative loss associated with a change in position (in dollars) in asset i, and $\tilde{\mathbf{x}}_t$ the portfolio positions in each asset *immediately before* that the transaction is performed at time t. This position is different from $\mathbf{x}_{t-1}$ because of the asset returns generated during period t

$$\tilde{x}_{it} = (r_{it} + 1) \, x_{i(t-1)}. \tag{23}$$

In our experiments, the transaction costs were set uniformly to 0.1%.

G. Volatility Estimation

As (16) shows, the covariance matrix $\boldsymbol{\Gamma}_t$ plays a fundamental role in computing the value at risk of a portfolio (under the normal approximation). It is therefore of extreme importance to make use of a good estimator for this covariance matrix.

For this purpose, we used an exponentially weighted moving average (EWMA) estimator, of the kind put forward by Risk-

Metrics [12]. Given an estimator of the covariance matrix at time $t-1$, a new estimate is computed by

$$\hat{\boldsymbol{\Gamma}}_t = \lambda \hat{\boldsymbol{\Gamma}}_{t-1} + (1-\lambda)(\mathbf{r}_t \mathbf{r}_t') \tag{24}$$

where $\mathbf{r}_t$ is the vector of asset returns over period t and λ is a *decay factor* that controls the speed at which observations are "absorbed" by the estimator. We used the value recommended by RiskMetrics for monthly data, $\lambda = 0.97$.

III. Neural Networks for Portfolio Management

The use of adaptive decision systems, such as neural networks, to implement asset-allocation systems is not new. Most applications of them fall into two categories: 1) using the neural net as a forecasting model, in conjunction with an allocation scheme (such as mean-variance allocation) to make the final decision; and 2) using the neural net to directly make the asset allocation decisions. We start by setting some notation related to our use of neural networks, and we then consider these two approaches in the context of portfolio selection subject to VaR constraints.

A. Neural Networks

We consider a specific type of neural network, the multilayer perceptron (MLP) with one hidden Tanh layer (with H hidden units), and a linear output layer. We denote by $f : \mathbb{R}^M \mapsto \mathbb{R}^N$ the vectorial function represented by the MLP. Let $\mathbf{x} (\in \mathbb{R}^M)$ be an input vector; the function is computed by the MLP as follows:

$$f(\mathbf{x}; \boldsymbol{\theta}) = \mathbf{A}_2 \tanh(\mathbf{A}_1 \mathbf{x} + \mathbf{b}_1) + \mathbf{b}_2. \tag{25}$$

The adjustable parameters of the network are: $\mathbf{A}_1$, an $H \times M$ matrix; $\mathbf{b}_1$ an H-element vector; $\mathbf{A}_2$ an $N \times H$ matrix; and $\mathbf{b}_2$ an N-element vector. We denote by $\boldsymbol{\theta}$ the vector of all parameters

$$\boldsymbol{\theta} = \langle \mathbf{A}_1, \mathbf{A}_2, \mathbf{b}_1, \mathbf{b}_2 \rangle.$$

1) Network Training: The parameters $\boldsymbol{\theta}$ are found by training the network to minimize a cost function, which depends, as we shall see below, on the type of model—forecasting or decision—that we are using. In our implementation, the optimization is carried out using a conjugate gradient descent algorithm [13]. The gradient of the parameters with respect to the cost function is computed using the standard backpropagation algorithm [14] for MLPs.

B. Forecasting Model

The forecasting model centers around a general procedure whose objective is to find an "optimal" allocation of assets, one which maximizes the expected value of a utility function (fixed *a priori*, and specific to each investor), given a probability distribution of asset returns.

The use of the neural network within the forecasting model is illustrated in Fig. 1(a). The network is used to make forecasts of asset returns in the next time period, $\hat{\boldsymbol{\mu}}_{t+1|t}$, given explanatory variables $\mathbf{u}_t$, which are described in Section V-A (these variables are determined causally, i.e., they are a function of $\mathcal{I}_t$.)

1) Maximization of Expected Utility: We assume that an investor associates a utility function $U(\mathbf{r}_{t+1}, \mathbf{w}_t)$ with the performance of his/her investment in the portfolio $\mathbf{w}_t$ over period $t+1$. (For the remainder of this section, we suppose, without loss of generality, that the net capital in a portfolio has been factored out of the equations; we use $\mathbf{w}_t$ to denote a portfolio whose elements sum to one.)

The problem of (myopic) utility maximization consists, at each time-step t, in finding the porfolio $\mathbf{w}_t$ that maximizes the expected utility obtained at $t+1$, given the information available at time t

$$\mathbf{w}_t^* = \underset{\mathbf{w}_t}{\operatorname{argmax}} \ \mathrm{E}[U(\mathbf{R}_{t+1}, \mathbf{w}_t) \,|\, \mathcal{I}_t]. \tag{26}$$

This procedure is called myopic because we only seek to maximize the expected utility over the next period, and not over the entire sequence of periods until some end-of-times.

The expected utility can be expressed in the form of an integral

$$\mathrm{E}[U(\mathbf{R}_{t+1}, \mathbf{w}_t) \,|\, \mathcal{I}_t] = \int_{\mathbf{R}_{t+1}} P_{t+1|t}(\mathbf{r})\, U(\mathbf{r}, \mathbf{w}_t)\, d\mathbf{r} \tag{27}$$

where $P_{t+1|t}(\cdot)$ is the probability density function of the asset returns, $\mathbf{R}_{t+1}$, given the information available at time t.

2) Quadratic Utility: Some "simple" utility functions admit analytical solutions for the expected utility (27). To derive the mean-variance allocation equations, we shall postulate that investors are governed by a quadratic utility of the form

$$U(\mathbf{R}_{t+1}, \mathbf{w}_t) = \mathbf{R}_{t+1}' \mathbf{w}_t - \lambda (\mathbf{w}_t' (\mathbf{R}_{t+1} - \boldsymbol{\mu}_{t+1}))^2. \tag{28}$$

The parameter $\lambda > 0$ represents the risk aversion of the investor; more risk-averse investors will choose higher λ's.

Assuming the first and second moment of the conditional distribution of asset returns exist, and writing them $\boldsymbol{\mu}_{t+1}$ and $\boldsymbol{\Gamma}_{t+1}$ respectively (with $\boldsymbol{\Gamma}_{t+1}$ positive-definite), (28) can be integrated out analytically to give the expected quadratic utility

$$\mathrm{E}[U(\mathbf{R}_{t+1}, \mathbf{w}_t) \,|\, \mathcal{I}_t] = \boldsymbol{\mu}_{t+1}' \mathbf{w}_t - \lambda \mathbf{w}_t' \boldsymbol{\Gamma}_{t+1} \mathbf{w}_t. \tag{29}$$

Substituting estimators available at time t, we obtain an estimator of the expected utility at time $t+1$

$$\hat{U}_{t+1}(\mathbf{w}_t) = \hat{\boldsymbol{\mu}}_{t+1|t}' \mathbf{w}_t - \lambda \mathbf{w}_t' \hat{\boldsymbol{\Gamma}}_{t+1|t} \mathbf{w}_t. \tag{30}$$

(We abuse slightly the notation here by denoting by $\hat{U}$ the estimator of *expected* utility.)

3) Mean-variance allocation: We now derive, under quadratic utility, the portfolio allocation equation. We seek a vector of "optimal" weights $\mathbf{w}_t^*$ that will yield the maximum expected utility at time $t+1$, given the information at time t.

Note that we can derive an analytical solution to this problem because we allow the weights to be negative as well as positive; the only constraint that we impose on the weights is that they sum to one (all the capital is invested). In contrast, the classical Markowitz formulation [15] further imposes the *positivity* of the weights; this makes the optimization problem tractable only by computational methods, such as quadratic programming.

We start by forming the Lagrangian incorporating the sum-to-one constraint to (29), observing that maximizing this

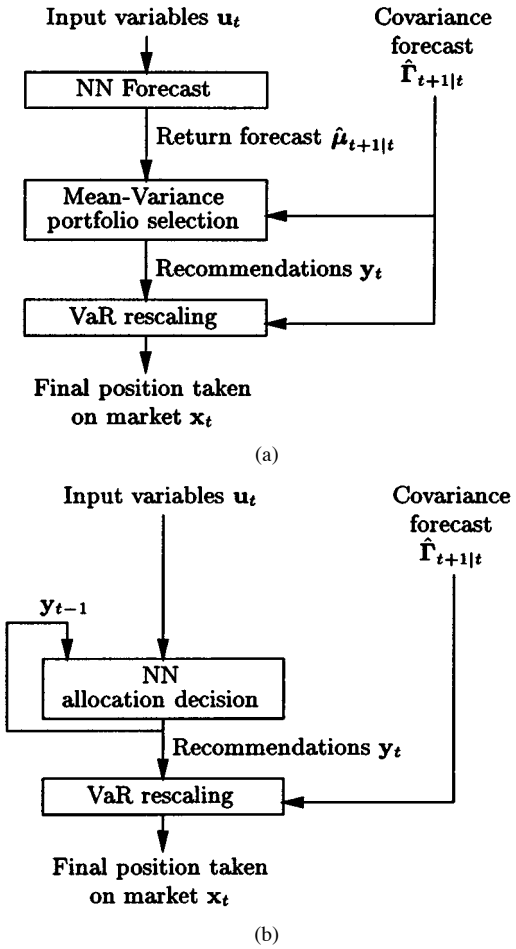

Fig. 1. The forecasting (a) and decision (b) paradigms for using neural networks (NN) in asset allocation.

equation is equivalent to minimizing its negative (ι is the vector $(1,\ldots,1)'$)

$$\mathcal{L}(\mathbf{w}_t,\alpha) = -\boldsymbol{\mu}'_{t+1}\mathbf{w}_t + \lambda \mathbf{w}'_t \boldsymbol{\Gamma}_{t+1}\mathbf{w}_t + \alpha(\mathbf{w}'_t\iota - 1). \quad (31)$$

After differentiating this equation and a bit of algebra, we find

$$\mathbf{w}^*_t = \frac{1}{\lambda}\boldsymbol{\Gamma}^{-1}_{t+1}\left(\boldsymbol{\mu}_{t+1} - \frac{\iota'\boldsymbol{\Gamma}^{-1}_{t+1}\boldsymbol{\mu}_{t+1} - \lambda}{\iota'\boldsymbol{\Gamma}^{-1}_{t+1}\iota}\,\iota\right). \quad (32)$$

In practical use, we have to substitute estimators available at time t for the parameters $\boldsymbol{\mu}_{t+1}$ and $\boldsymbol{\Gamma}_{t+1}$ in this equation.

To recapitulate, the "optimal" weight vector $\mathbf{w}^*_t$ constitutes the *recommendations vector* $\mathbf{y}_t$ output by the mean-variance allocation module in Fig. 1(a).

4) MLP Training Cost Function: As illustrated in Fig. 1(a), the role played by the neural network in the forecasting model is to produce estimates of the mean asset returns over the next period. This use of a neural net is all-the-more classical, and hence the training procedure brings no surprise.

The network is trained to minimize the prediction error of the realized asset returns, using a quadratic loss function

$$C_{\mathsf{F}}(\boldsymbol{\theta}) = \frac{1}{T}\sum_{t=1}^{T} \|f(\mathbf{u}_t;\boldsymbol{\theta}) - \mathbf{r}_{t+1}\|^2 + C_{\mathsf{WD}}(\boldsymbol{\theta}) + C_{\mathsf{ID}}(\boldsymbol{\theta}) \quad (33)$$

where $\|\cdot\|$ is the Euclidian distance, and $f(\cdot;\boldsymbol{\theta})$ is the function computed by the MLP, given the parameter vector $\boldsymbol{\theta}$. The $C_{\mathsf{WD}}(\boldsymbol{\theta})$ and $C_{\mathsf{ID}}(\boldsymbol{\theta})$ terms serve regularization purposes; they are described in Section IV.

As explained above, the network is trained to minimize this cost function using a conjugate gradient optimizer, with gradient information computed using the standard backpropagation algorithm for MLPs.

C. Decision Model

Within the decision model, in contrast with the forecasting model introduced previously, the neural network directly yields the allocation recommendations $\mathbf{y}_t$ from explanatory variables $\mathbf{u}_t$ [Fig. 1(b)].

We introduce the possibility for the network to be *recurrent*, taking as input the recommendations emitted during the previous time step. This enables, in theory, the network to make decisions that would not lead to excess trading, to minimize transaction costs.

1) Justifying The Model: Before explaining the technical machinery necessary for training the recurrent neural network in the decision model, we provide a brief explanation as to why such a network would be attractive. We note immediately that, as a downside for the model, the steps required to produce a decision are not as "transparent" as they are for the forecasting model: everything happens inside the "black box" of the neural network. However, from a pragmatic standpoint, the following reasons lead us to believe that the model's potential is at least worthy of investigation:

- The probability density estimation problem—which must be solved in one way or another by the forecasting model—is intrinsically a very difficult problem in high dimension [16]. The decision model does not require an explicit solution to this problem (although some function of the density is learned implicitly by the model).
- The decision model does not need to explicitly postulate a utility function that admits a simple mathematical treatment, but which may not correspond to the needs of the investor. The choice of this utility function is important, for it directly leads to the allocation decisions within the forecasting model. However, we already know, without deep analysis, that quadratic utility does not constitute the "true" utility of an investor, for the sole reasons that it treats good news just as negatively as bad news (because both lead to high variance), and does not consider transaction costs. Furthermore, the utility function of the forecasting model is not the final financial criterion (18) on which it is ultimately evaluated. In contrast, the decision model directly maximizes this criterion.

2) Training Cost Function: The network is trained to directly minimize the (negative of the) financial performance evaluation criterion (18):

$$C_{\mathsf{D}}(\boldsymbol{\theta}) = -\frac{1}{T}\sum_{t=1}^{T} W_t + C_{\mathsf{WD}}(\boldsymbol{\theta}) + C_{\mathsf{ID}}(\boldsymbol{\theta}) + C_{\mathsf{norm}}. \quad (34)$$

The terms $C_{\mathsf{WD}}(\boldsymbol{\theta})$ and $C_{\mathsf{ID}}(\boldsymbol{\theta})$, which are the same as in the forecasting model cost function, are described in Section IV.

The new term C_{norm} induces a preference on the norm of the solutions produced by the neural network; its nature is explained shortly.

The effect of this cost function is to have the network learn to maximize the profit returned by a VaR-constrained portfolio.

3) Training the MLP: The training procedure for the MLP is quite more complex for the decision model than it is for the forecasting model: the feedback loop, which provides as inputs to the network the recommendations $\mathbf{y}_{t-1}$ produced for the preceding time step, induces a recurrence which must be accounted for. This feedback loop is required for the following reasons.

- The transaction costs introduce a coupling between two successive time steps: the decision made at time t has an impact on both the transaction costs incurred at t and at $t+1$. This coupling induces in turn a gradient with respect to the positions $\mathbf{x}_t$ coming from the positions $\mathbf{x}_{t+1}$, and this information can be of use during training. We explain these dependencies more deeply in the following section.
- In addition, knowing the decision made during the preceding time step can enable the network to learn a strategy that minimizes the transaction costs: given a choice between two equally profitable positions at time t, the network can minimize the transaction costs by choosing that closer to the position taken at time $t-1$; for this reason, providing $\mathbf{y}_{t-1}$ as input can be useful. Unfortunately, this ideal of minimizing costs can never be reached perfectly, because our current process of rescaling the positions at each time step for reaching the target VaR is always performed *unconditionally*, i.e., oblivious to the previous positions.

4) Backpropagation Equations: We now introduce the backpropagation equations. We note that these equations shall be, for a short moment, slightly incomplete: we present in the following section a regularization condition that ensures the existence of local minima of the cost function.

The backpropagation equations are obtained in the usual way, by traversing the flow graph of the allocation system, unfolded through time, and by accumulating all the contributions to the gradient at a node. Fig. 2 illustrates this graph, unfolded for the first few time steps. Following the backpropagation-through-time (BPTT) algorithm [14], we compute the gradient by going back in time, starting from the last time step T until the first one.

Recall that we denote by $f(\cdot;\boldsymbol{\theta})$ the function computed by a MLP with parameter vector $\boldsymbol{\theta}$. In the decision model, the allocation recommendations $\mathbf{y}_t$ are the direct product of the MLP

$$\mathbf{y}_t = f(\mathbf{y}_{t-1}, \mathbf{u}_t; \boldsymbol{\theta}) \tag{35}$$

where $\mathbf{u}_t$ are explanatory variables considered useful to the allocation problem, which we can compute given the information set $\mathcal{I}_t$.

We shall consider a slightly simpler criterion C to minimize than (34), one that does not include any regularization term. As we shall see below, incorporating those terms involves trivial modifications to the gradient computation. Our simplified criterion C (illustrated in the lower right-hand side of Fig. 2) is

$$C = -\hat{W}. \tag{36}$$

From (18), we account for the contribution brought to the criterion by the profit at each time step

$$\frac{\partial C}{\partial \hat{W}_{t+1}} = -\frac{1}{T}. \tag{37}$$

Next, we make use of (19), (22) and (23) to determine the contribution of transaction costs to the gradient

$$\frac{\partial C}{\partial \text{loss}_t} = -\frac{1}{T\tilde{V}_t} \tag{38}$$

$$\frac{\partial \text{loss}_t}{\partial x_{it}} = -c_i \operatorname{sign}(x_{it} - \tilde{x}_{it}) \tag{39}$$

$$\frac{\partial \text{loss}_t}{\partial \tilde{x}_{it}} = c_i \operatorname{sign}(x_{it} - \tilde{x}_{it}) \tag{40}$$

$$\begin{aligned}\frac{\partial \text{loss}_{t+1}}{\partial x_{it}} &= c_i \operatorname{sign}(x_{i(t+1)} - \tilde{x}_{i(t+1)}) \frac{\partial \tilde{x}_{i(t+1)}}{\partial x_{it}} \\ &= c_i \operatorname{sign}(x_{i(t+1)} - \tilde{x}_{i(t+1)})(1 + r_{i(t+1)}).\end{aligned} \tag{41}$$

From this point, again making use of (19), we compute the contribution of x_{it} to the gradient, which comes from the two "paths" by which x_{it} affects C: a first direct contribution through the return between times t and $t+1$; and a second indirect contribution through the transaction costs at $t+1$

$$\frac{\partial C}{\partial x_{it}} = \frac{\partial C}{\partial \hat{W}_{t+1}} \frac{\partial \hat{W}_{t+1}}{\partial x_{it}} + \frac{\partial C}{\partial \hat{W}_{t+2}} \frac{\partial \hat{W}_{t+2}}{\partial x_{it}}. \tag{42}$$

Because $\partial C / \partial \hat{W}_{t+1}$ is simply given by (37), we use (19) to compute

$$\frac{\partial C}{\partial \hat{W}_{t+1}} \frac{\partial \hat{W}_{t+1}}{\partial x_{it}} = -\frac{1}{T\tilde{V}_t}\left(r_{i(t+1)} - r_{0t} + \frac{\partial \text{loss}_t}{\partial x_{it}}\right) \tag{43}$$

whence

$$\frac{\partial C}{\partial \hat{W}_{t+1}} \frac{\partial \hat{W}_{t+1}}{\partial x_{it}} = -\frac{1}{T\tilde{V}_t}(r_{i(t+1)} - r_{0t} - c_i \operatorname{sign}(x_{it} - \tilde{x}_{it})). \tag{44}$$

In the same manner, we compute the contribution

$$\frac{\partial C}{\partial \hat{W}_{t+2}} \frac{\partial \hat{W}_{t+2}}{\partial x_{it}} = -\frac{1}{T\tilde{V}_{t+1}} \frac{\partial \text{loss}_{t+1}}{\partial x_{it}} \tag{45}$$

which gives, after simplification,

$$\begin{aligned}\frac{\partial C}{\partial \hat{W}_{t+2}} \frac{\partial \hat{W}_{t+2}}{\partial x_{it}} = -\frac{1}{T\tilde{V}_{t+1}}&(c_i \operatorname{sign}(x_{i(t+1)} - \tilde{x}_{i(t+1)}) \\ &\cdot (1 + r_{i(t+1)})).\end{aligned} \tag{46}$$

Finally, we add up the two previous equations to obtain

$$\begin{aligned}\frac{\partial C}{\partial x_{it}} = &-\frac{1}{T\tilde{V}_t}(r_{i(t+1)} - r_{0t} - c_i \operatorname{sign}(x_{it} - \tilde{x}_{it})) \\ &- \frac{1}{T\tilde{V}_{t+1}}(c_i \operatorname{sign}(x_{i(t+1)} - \tilde{x}_{i(t+1)})(1 + r_{i(t+1)})).\end{aligned} \tag{47}$$

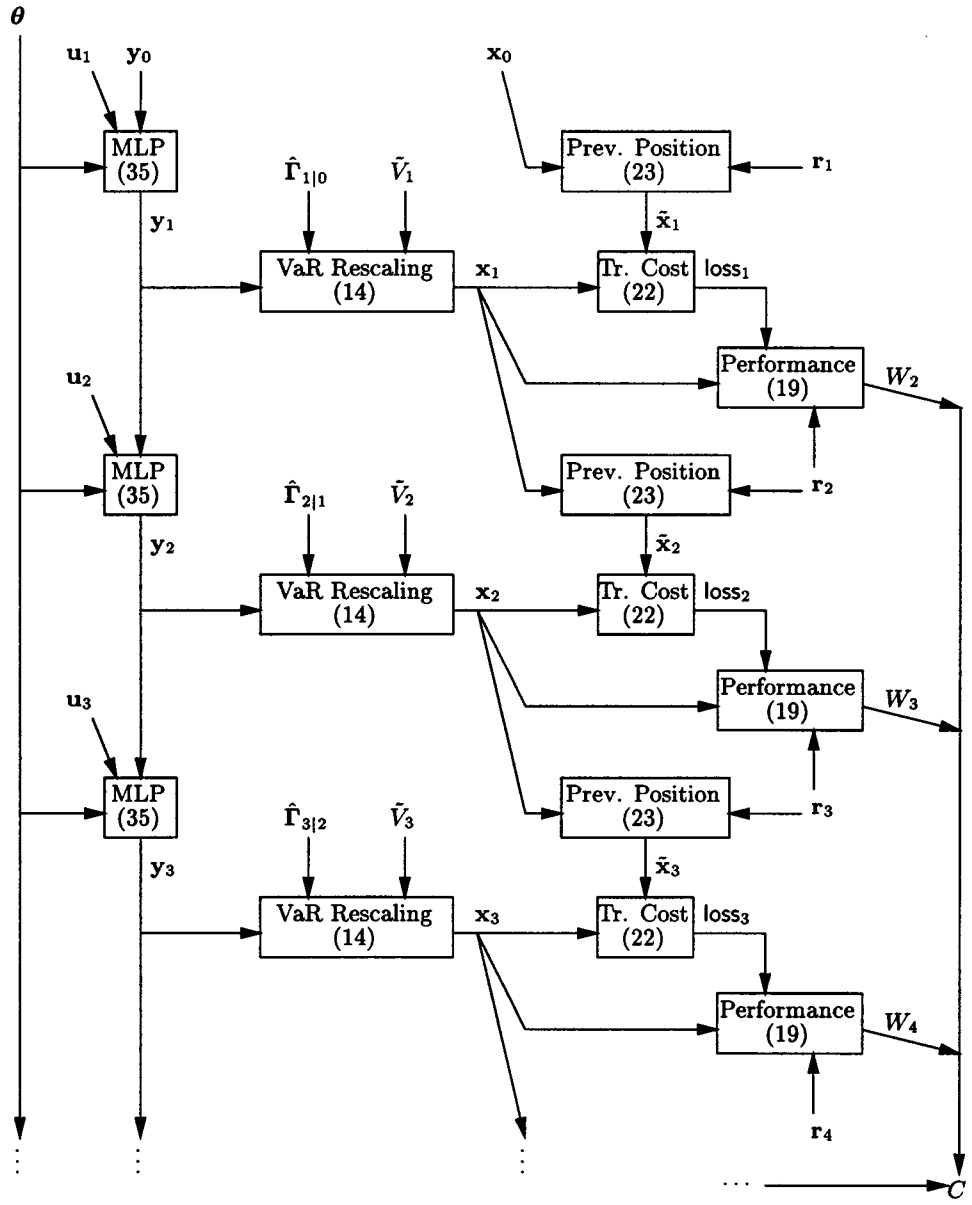

Fig. 2. Flow graph of the steps implemented by the decision model, unfolded through time. The backpropagation equations are obtained by traversing the graph in the reverse direction of the arrows. The numbers in parentheses refer to the equations (in the main text) used for computing each value.

We are now in a position to compute the gradient with respect to the neural-network outputs. Using (14) and (16), we start by evaluating the effect of y_{it} on x_{it}:[1]

$$\frac{\partial x_{it}}{\partial y_{it}} = \frac{\tilde{V}_t}{\Phi^{-1}(\alpha)(\mathbf{y}_t'\hat{\boldsymbol{\Gamma}}_{t+1|t}\mathbf{y}_t)^{1/2}} - \frac{y_{it}\,\tilde{V}_t \sum_{k=1}^{N} \hat{\gamma}_{ik(t+1)} y_{kt}}{\Phi^{-1}(\alpha)\,(\mathbf{y}_t'\hat{\boldsymbol{\Gamma}}_{t+1|t}\mathbf{y}_t)^{3/2}} \tag{48}$$

and for $i \neq j$

$$\frac{\partial x_{it}}{\partial y_{jt}} = -\frac{y_{it}\,\tilde{V}_t \sum_{k=1}^{N} \hat{\gamma}_{ik(t+1)} y_{kt}}{\Phi^{-1}(\alpha)\,(\mathbf{y}_t'\hat{\boldsymbol{\Gamma}}_{t+1|t}\mathbf{y}_t)^{3/2}}. \tag{49}$$

(As previously noted, α is the desired level of the VaR, and $\Phi^{-1}(\cdot)$ is the inverse cumulative distribution function of the standardized normal distribution.)

The complete gradient is given by

$$\frac{\partial C}{\partial y_{it}} = \sum_k \frac{\partial C}{\partial x_{kt}} \frac{\partial x_{kt}}{\partial y_{it}} + \frac{\partial C}{\partial f_{t+1}} \tag{50}$$

where $\partial C/\partial f_{t+1}$ is the gradient with respect to the inputs of the neural network at time $t+1$, which is a usual by-product of the standard backpropagation algorithm.

[1]To arrive at these equations, it is useful to recall that $\mathbf{y}'\boldsymbol{\Gamma}\mathbf{y}$ can be written in the form of $\sum_k \sum_\ell \gamma_{k\ell}\, y_k\, y_\ell$, whence it easily follows that $(\partial/\partial y_i)\mathbf{y}'\boldsymbol{\Gamma}\mathbf{y} = 2\sum_k \gamma_{ik}\, y_k$.

5) Introducing a "Preferred Norm": The cost function (36) corresponding to the financial criterion (18) cannot reliably be used in its original form to train a neural network. The reason lies in the rescaling (14) and (16) that transform a recommendation vector $\mathbf{y}_t$ into a VaR-constrained portfolio $\mathbf{x}_t$. Consider two recommendations $\mathbf{y}_t^{(1)}$ and $\mathbf{y}_t^{(2)}$ that differ only by a multiplicative factor $\delta > 0$

$$\mathbf{y}_t^{(2)} = \delta \mathbf{y}_t^{(1)}.$$

As can easily be seen by substitution in the rescaling equations, the final porfolios obtained from those two (different) recommendations are identical! Put differently, two different recommendations that have the same direction but different lengths are rescaled into the same final portfolio.

This phenomenon is illustrated in Fig. 3, which shows the level curves of the cost function for a small allocation problem between two assets (stocks and bonds, in this case), as a function of the *recommentations* output by the network. We observe clearly that different recommendations in the same direction yield the same cost.

The direct consequence of this effect is that the optimization problem for training the parameters of the neural network is not well posed: two different sets of parameters yielding equal solutions (within a constant factor) will be judged as equivalent by the cost function. This problem can be expressed more precisely as follows: for nearly every parameter vector $\boldsymbol{\theta}$, there is a direction from that point that has (exactly) zero gradient, and hence there is no local minimum in that direction. We have observed empirically that this could lead to severe divergence problems when the network is trained with the usual gradient-based optimization algorithms such as conjugate gradient descent.

This problem suggests that we can introduce an *a priori* preference on the norm of the recommendations, using a modification to the cost function that is analogous to the "hints" mechanism that is sometimes used for incorporating *a priori* knowledge in neural-network training [17]. This preference is introduced by way of a soft constraint, the regularization term C_{norm} appearing in (34)

$$C_{\text{norm}} = \frac{\phi_{\text{norm}}}{2T} \sum_{t=1}^{T} \left(\sum_{i=1}^{N} y_i^2 - \rho^2 \right)^2. \tag{51}$$

Two parameters must be determined by the user: 1) ρ, which is the desired norm for the recommendations output by the neural network (in our experiments, it was arbitrarily set to $\rho^2 = 0.9$) and 2) ϕ_{norm}, which controls the relative importance of the penalization in the total cost.

Fig. 4 illustrates the cost function modified to incorporate this penalization (with $\rho^2 = 0.9$ and $\phi_{\text{norm}} = 0.1$). We now observe the clear presence of local minima in this function. The optimal solution is in the same direction as previously, but it is now encouraged to have a length ρ.

This penalization brings forth a small change to the backpropagation equations introduced previously: the term $\partial C/\partial y_{it}$, (50), must be adjusted to become

$$\frac{\partial C'}{\partial y_{it}} = \frac{\partial C}{\partial y_{it}} + \frac{\phi_{\text{norm}}}{T} \left(\sum_{j=1}^{N} y_{jt}^2 - \rho^2 \right) (2y_{it}). \tag{52}$$

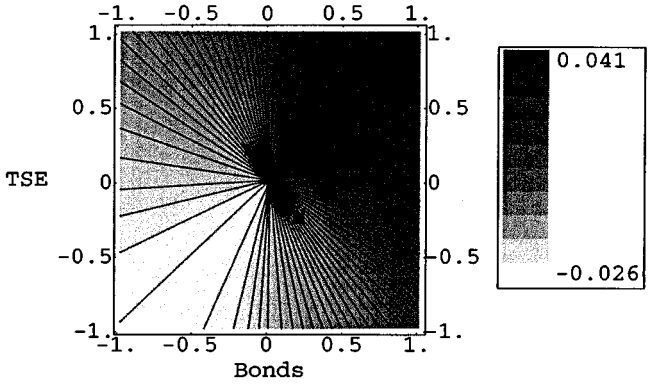

Fig. 3. Level curves of the nonregularized cost function for a two-asset allocation problem. The axes indicate the value of each component of a *recommendation*. There is no minimum point to this function, but rather a half-line of minimal cost, starting around the origin toward the bottom left. This is undesirable, since it may lead to numerical difficulties when optimizing the VaR criterion.

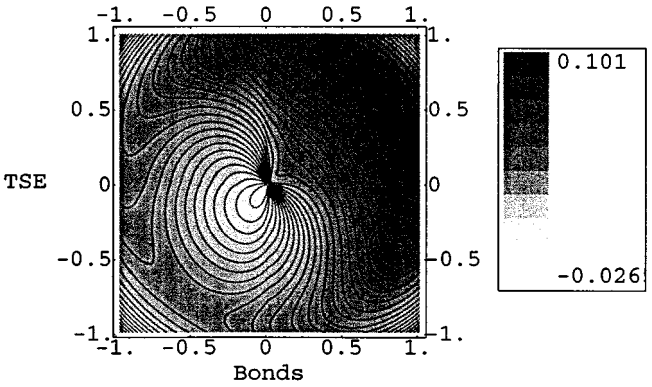

Fig. 4. Level curves of the regularized cost function for the two-asset problem. The "preferred" norm of the recommendations has been fixed to $\rho^2 = 0.9$. In contrast to Fig. 3, a minimum can clearly be seen a bit to the left and below the origin (i.e., along the minimum half-line of Fig. 3). This regularized cost function yields a better-behaved optimization process.

6) Reference Portfolio: A second type of preference takes the form of a *preferred portfolio:* in some circumstances, we may know *a priori* what should be "good positions" to take, often because of regulatory constraints. For instance, a portfolio manager may be mandated to construct her portfolio such that it contains "approximately" 60% stocks and 40% bonds. This contraint, which results from policies on which the manager has no immediate control, constitutes the reference portfolio.

We shall denote this reference portfolio by $\boldsymbol{\psi}_t$. The cost function (34) is modified to replace the C_{norm} term by a $C_{\text{ref.port.}}$ term that penalizes the squared-distance between the network output and the reference portfolio

$$C_{\text{ref.port.}} = \frac{1}{T} \sum_{t=1}^{T} \text{penalty}_{\text{ref.port.}}(\mathbf{y}_t) \tag{53}$$

$$\text{penalty}_{\text{ref.port.}}(\mathbf{y}_t) = \frac{\phi_{\text{ref.port.}}}{2} ||\mathbf{y}_t - \boldsymbol{\psi}_t||^2 \tag{54}$$

with $||\cdot||$ the Euclidian distance.

With this change, the backpropagation equations are simple to adjust; we add a contribution to $\partial C/\partial y_{it}$, (50), which becomes

$$\frac{\partial C_{\text{ref.port.}}}{\partial y_{it}} = \frac{\partial C}{\partial y_{it}} + \frac{\phi_{\text{ref.port.}}}{T}(y_{it} - \psi_{it}). \tag{55}$$

In our experiments with the TSE 300 sectors (see Section V), we favored this reference-portfolio penalization over the preferred-norm penalization. Our reference portfolio was chosen to be the market weight of each sector with respect to the complete TSE index; the $\phi_{\text{ref.port.}}$ hyper-parameter was set to a constant 0.1.

D. Why Optimize the VaR Criterion?

It is tempting to associate the optimization criterion for training the neural network (34) to the maximization of the Sharpe ratio, as is done in, e.g., [2], [3]. However, even though the criterion indeed appears superficially similar to the Sharpe ratio, it brings more flexibility in the modeling process.

1) The variance used in the Sharpe ratio measure is the (single) estimated variance over the entire training set, whereas criterion (34) uses, for each timestep, an estimator of the variance for the following timestep. (In our experiments, this estimator was, for simplicity, the EWMA estimator, but in general it could be a much better forecast.)
2) Criterion (34) allows time-varying risk exposures, for instance to compensate for inflation or changing market conditions. In our experiments, this was set to a constant \$1 VaR, but it can easily be made to vary with time.

IV. Regularization, Hyperparameter Selection, and Model Combination

Regularization techniques are used to specify *a priori* preferences on the network weights; they are useful to control network capacity to help prevent overfitting. In our experiments, we made use of two such methods, weight decay and input decay (in addition, for the decision model, to the norm preference covered previously.)

A. Weight Decay

Weight decay is a classic regularization procedure that imposes a penalty to the squared norm of all network weights

$$C_{\text{WD}}(\boldsymbol{\theta}) = \frac{\phi_{\text{WD}}}{2} \sum_k \theta_k^2 \tag{56}$$

where the summation is performed over all the elements of the parameter vector $\boldsymbol{\theta}$ (in our experiments, the biases, e.g., $\mathbf{b}_1$ and $\mathbf{b}_2$ in (25), were omitted); ϕ_{WD} is a hyperparameter (usually determined through trial-and-error, but not in our case as we shall see shortly) that controls the importance of C_{WD} in the total cost.

The effect of weight decay is to encourage the network weights to have smaller magnitudes; it reduces the learning capacity of the network. Empirically, it often yields improved generalization performance when the number of training examples is relatively small [18]. Its disadvantage is that it does not take into account the function to learn: it applies without discrimination to every weight.

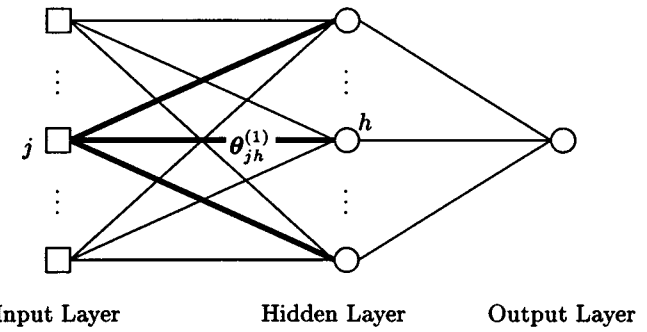

Fig. 5. Soft variable selection: illustration of the network weights affected by the input decay penalty term $C_{\text{ID}}^{(j)}(\boldsymbol{\theta})$, for an input j in a one-hidden-layer MLP (thick lines).

B. Input Decay

Input decay is a method for performing "soft" variable selection during the regular training of the neural network. Contrarily to combinatorial methods such as branch-and-bound and forward or backward selection, we do not seek a "good set" of inputs to provide to the network; we provide them all. The network will automatically penalize the network connections coming from the inputs that turn out not to be important.

Input decay works by imposing a penalty to the squared-norm of the weights linking a particular network input to all hidden units. Let $\theta_{jh}^{(1)}$ the network weight (located on the first layer of the MLP) linking input j to hidden unit h; the squared-norm of the weights from input j is

$$C_{\text{ID}}^{(j)}(\boldsymbol{\theta}) = \sum_{h=1}^{H} (\theta_{jh}^{(1)})^2 \tag{57}$$

where H is the number of hidden units in the network. The weights that are part of $C_{\text{ID}}^{(j)}(\boldsymbol{\theta})$ are illustrated in Fig. 5.

The complete contribution $C_{\text{ID}}(\boldsymbol{\theta})$ to the cost function is obtained by a nonlinear combination of the $C_{\text{ID}}^{(j)}$

$$C_{\text{ID}}(\boldsymbol{\theta}) = \phi_{\text{ID}} \sum_j \frac{C_{\text{ID}}^{(j)}}{\eta + C_{\text{ID}}^{(j)}(\boldsymbol{\theta})} \tag{58}$$

The behavior of the function $x^2/(\eta + x^2)$ is shown in Fig. 6. Intuitively, this function acts as follows: if the weights emanating from input j are small, the network must absorbe a high marginal cost (locally quadratic) in order to increase the weights; the net effect, in this case, is to bring those weights closer to zero. On the other hand, if the weights associated with that input have become large enough, the penalty incurred by the network turns into a constant independent of the value of the weights; those are then free to be adjusted as appropriate. The parameter η acts as a threshold that determines the point beyond which the penalty becomes constant.

Input decay is similar to the *weight elimination* procedure [9] sometimes applied for training neural networks, with the difference that input decay applies in a collective way to the weights associated with a given input.

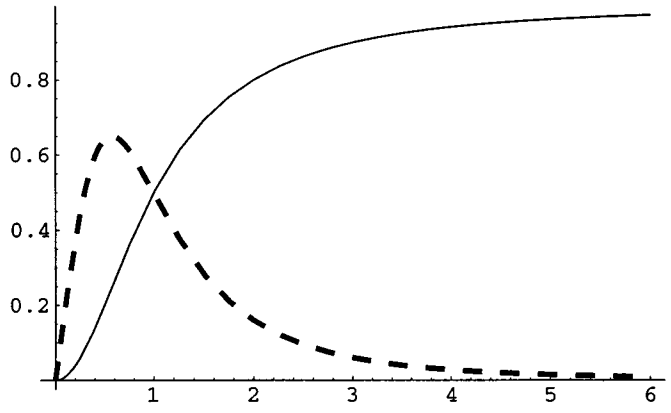

Fig. 6. Soft variable selection: shape of the penalty function $x^2/(\eta + x^2)$ (solid), and its first derivative (dashed), for $\eta = 1$.

C. Model Combination

The capacity-control methods described above leave open the question of selecting good values for the hyperparameters ϕ_{WD} and ϕ_{ID}. These parameters are normally chosen such as to minimize the error on a validation set, separate from the testing set. However, we found desirable to completely avoid using a validation set, primarily because of the limited size of our data sets. Since we are not in a position to *choose* the best set of hyperparameters, we used model combination methods to altogether avoid having to make a choice.

We use model combination as follows. We have M underlying models, sharing the same basic MLP topology (number of hidden units) but varying in the hyperparameters. Each model m implements a function $f_{mt}(\cdot)$.[2] We construct a *committee* whose decision is a convex combination of the underlying decisions

$$\mathbf{y}_t^{\mathsf{com}} = \sum_{m=1}^{M} w_{mt}\, f_{mt}(\mathbf{u}_t) \tag{59}$$

with $\mathbf{u}_t$ the vector of explanatory variables, and $w_{mt} \geq 0$, $\sum_m w_{mt} = 1$. The weight given to each model depends on the combination method; intuitively, models that have "worked well" in the past should be given greater weight. We consider three such combination methods: hardmax, softmax, and exponentiated gradient.

1) Hardmax: The simplest combination method is to choose, at time t, the model that yielded the *best generalization performance* (out-of-sample) for all (available) preceding time steps. We assume that a generalization performance result is available for all time steps from $G+1$ until $t-1$ (where t is the current time step).[3]

Let $\hat{W}_m(\tau)$ the (generalization) financial performance returned during period τ by the mth member of the committee. Let m_t^* the "best model" until time $t-1$

$$m_t^* = \operatorname*{argmax}_m \sum_{\tau=G+1}^{t-1} \hat{W}_m(\tau). \tag{60}$$

[2]Because of the retrainings brought forth by the sequential validation procedure described in Section IV-D, the function realized by a member of the committee has a time dependency.

[3]We shall see in Section IV-D that this out-of-sample performance is available, for all time steps beyond an initial training set, by using the sequential validation procedure described in that section.

The weight given at time t to the mth member of the committee by the hardmax combination method is

$$w_{mt}^{\mathsf{hardmax}} = \begin{cases} 1 & \text{if } m = m_t^*, \\ 0 & \text{otherwise.} \end{cases} \tag{61}$$

2) Softmax: The softmax method is a simple modification of the previous one. It consists in combining the average past generalization performances using the softmax function. Using the same notation as previously, let $\overline{W}_{mt}$ be the average financial performance obtained by the mth comittee member until time $t-1$

$$\overline{W}_{mt} = \frac{1}{t-G-1} \sum_{\tau=G+1}^{t-1} \hat{W}_m(\tau). \tag{62}$$

The weight given at time t to the mth member of the committee by the softmax combination method is

$$w_{mt}^{\mathsf{softmax}} = \frac{\exp(\overline{W}_{mt})}{\sum_{k=1}^{M} \exp(\overline{W}_{kt})}. \tag{63}$$

3) Exponentiated Gradient: We used the fixed-share version [20] of the exponentiated gradient algorithm [21]. This method uses an exponential update of the weights, followed by a redistribution step that prevents any of the weights from becoming too large. First, raw weights are computed from the "loss" (19) incurred in the previous time step

$$\tilde{w}_{mt} = w_{m(t-1)}\, e^{\delta W_t(f_{m(t-1)})}. \tag{64}$$

Next, a proportional share of the weights is taken and redistributed uniformly (a form of taxation) to produce new weights

$$\begin{aligned} \mathsf{pool}_t &= \sum_{m=1}^{M} \tilde{w}_{mt} \\ w_{mt}^{\mathsf{exp.grad.}} &= (1-\alpha)\tilde{w}_{mt} + \frac{1}{M-1}(\mathsf{pool}_t - \alpha\tilde{w}_{mt}). \end{aligned} \tag{65}$$

The parameters δ and α control, respectively, the convergence rate and the minimum value of a weight. Some experimentation on the initial training set revealed that $\delta = 0.3$, $\alpha = 0.01$ yielded reasonable behavior, but these values were not tuned extensively.

An extensive analysis of this combination method, including bounds on the generalization error, is provided by [20].

D. Performance Estimation for Sequential Decision Problems

Cross-validation is a performance-evaluation method commonly used when the total size of the data set is relatively small, *provided* that the data contains no temporal structure, i.e., the observations can be freely permuted. Since this is obviously not the case for our current asset-allocation problem, ordinary cross-validation is not applicable.

To obtain low-variance performance estimates, we use a variation on cross-validation called *sequential validation* that preserves the temporal structure of the data. Although a formal definition of the method can be given (e.g., [10]), an intuitive description is as follows:

1) An *initial training set* is defined, starting from the first available time step and extending until a predefined time G (included). A model of a given topology

$\mathcal{M}$ (fixing the number of hidden units, and the value of the hyperparameters) is trained on this initial data.

2) The model is tested on the P observations in the data set that *follow* after the end of the training set. The test result for each time step is computed using the financial performance criterion, (19). These test results are saved aside.

3) The P test observations used in Step 2 are added to the training set, and a model with the same topology $\mathcal{M}$ is retrained using the new training set.

4) Steps 2 and 3 are performed until the data set is exhausted.

5) The final performance estimate for the model with topology $\mathcal{M}$ for the entire data set is obtained by averaging the test results for all time steps saved in Step 2 [cf. (18)].

We observe that for every time step beyond G (the end of the initial training set), a generalization (out-of-sample) performance result is available for a given time step, even though the data for this time step might eventually become part of a later training set.

The "progression" factor P in the size of the training set is a free parameter of the method. If nonstationarities are suspected in the data set, P should be chosen as small as possible; the obvious downside is the greatly increased computational requirement incurred with a small P. In our experiments, we attempted to strike a compromise by setting $P = 12$, which corresponds to retraining every year for monthly data.

Finally, we note that the method of sequential validation owes its simplicity to the fact that the model combination algorithms described above (which can be viewed as performing a kind of model selection) operate strictly on in-sample data, and make use of out-of-sample data solely to calculate an unbiased estimate of the generalization error. Alternatively, model selection or combination can be performed after the fact, by choosing the model(s) that performed the best on *test* data; when such a choice is made, it is advisable to make use of a procedure proposed by White [22] to test whether the chosen models might have been biased by data snooping effects.

V. Experimental Results and Analysis

A. Overall Setting

Our experiments consisted in allocating among the 14 sectors (subindexes) of the Toronto Stock Exchange TSE 300 index. Each sector represents an important segment of the canadian economy. Our benchmark market performance is the complete TSE 300 index. (To make the comparisons meaningful, the market portfolio is also subjected to VaR constraints). We used monthly data ranging from January 1971 until July 1996 (no missing values). Our "risk-free" interest rate is that of the short-term (90-day) Canadian government T-bills.

To obtain a performance estimate for each model, we used the sequential validation procedure, by first training on 120 months and thereafter retraining every 12 months, each time testing on the 12 months following the last training point.

1) Inputs and Preprocessing: The input variables $\mathbf{u}_t$ provided to the neural networks consisted of the following:

- three series of 14 moving average returns (short-, mid-, and long-term MA depths);
- two series of 14 return volatilities (computed using exponential averages with a short-term and long-term decay);
- five series, each corresponding to the "instantaneous" average over the 14 sectors of the above series.

The resulting 75 inputs are then normalized to zero-mean and unit-variance before being provided to the networks.

2) Experimental Plan: The experiments that we performed are divided into two major parts, those with single models, and those with model combination. In all our experiments, we set a target VaR of \$1, with a probability of 95%.

a) Experiments with Single Models: The first set of experiments (Section V-B) is designed to understand the impact of the model type (and hence of the cost function used to train the neural network), of network topology and of capacity-control hyperparameters on the financial performance criterion. In this set, we consider the following.

- **Model type:** We compare 1) the decision model without network recurrence; 2i) the decision model with recurrence; 3) the forecasting model without recurrence.
- **Network topology:** For each model type, we evaluate the effect of the number of hidden units, from the set $NH \in \{2, 5, 10\}$.
- **Capacity control:** For each of the above cases, we evaluate the effects of the weight decay and input decay penalizations. Since we do not know *a priori* what are good settings for the hyperparameters, we train several networks, one for each combination of $\phi_{\mathsf{WD}} \in \{10^{-3}, 10^{-2}, 10^{-1}, 10^{0}\}$ and $\phi_{\mathsf{ID}} \in \{10^{-3}, 10^{-2}, 10^{-1}, 10^{0}\}$.

Our analysis in this section uses analyzes of variance (ANOVAs, briefly described below) and pairwise comparisons between single models in order to single out the most significant of the above factor(s) in determining performance. However, as pointed out in Section IV-C, selecting a "best model" from these results would amount to performing model selection on the test set (i.e., cheating), and hence we have to rely on model combination methods to truly estimate the real-world trading system performance.

b) Experiments with Model Combination: The second set of experiments (Section V-C) verifies the usefulness of the model combination methods. We construct committees that combine, for a given type of model, MLP's with the same number of hidden units but that vary in the setting of the hyperparameters controlling weight and input decay (ϕ_{WD} and ϕ_{ID}). Our analysis in this section focuses on:

- evaluating the relative effectiveness of the combination methods using statistical tests;
- comparing the performance of a committee with that of the underlying models making up the committee;
- ensuring that committees indeed reach their target value-at-risk levels.

B. Results with Single Models

We start by analyzing the generalization (out-of-sample) performance obtained by all single models on the financial perfor-

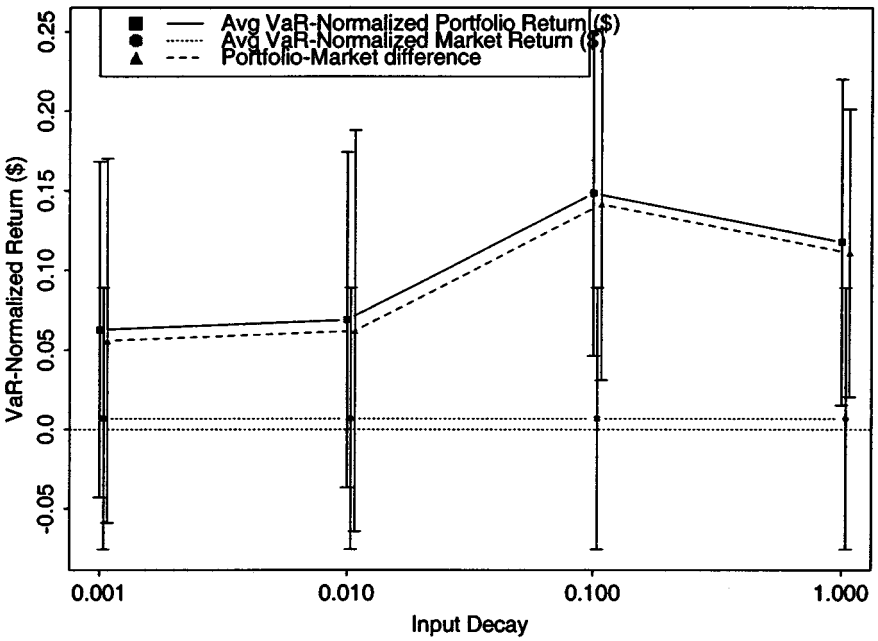

Fig. 7. Effect of input decay on the financial performance obtained by an MLP in an asset-allocation task (solid). The (constant) benchmark market performance is given (dotted), along with the MLP-market difference (dashed). The error bars represent 95% confidence intervals. We note that the use of input decay can significantly improve performance.

mance criterion. In all the results that follow, we reserve the term "significant" to denote statistical significance at the 0.05 level.

Detailed performance results for the individual models is presented elsewhere [10]. Comparing each model to the benchmark market performance[4] we observe that several of the single models are yielding net returns that are significantly better than the market.

Fig. 7 shows the impact of input decay on a cross-section of the experiments (in this case, the forecasting model with five hidden units, and constant $WD = 1.0$.) At each level of the input decay factor, the average performance (square markers) is given with a 95% confidence interval; the benchmark market performance (round markers) and the difference between the model and the benchmark (triangular markers) are also plotted.

1) ANOVA Results for Single Models: We further compared the single models using a formal analysis of variance (ANOVA) to detect the systematic impact of a certain factors. The ANOVA (e.g., [23]) is a well-known statistical procedure used to test the effect of several experimental factors (each factor taking several discrete levels) on a continuous measured quantity, in our case, a financial performance measure. The null hypothesis being tested is that the mean performance measure is identical for all levels of the factors under consideration.

The results are given in Tables I–III, respectively, for the decision model without and with recurrence, and for the forecasing model. We make the following observations:

- for all the model types, the input decay factor has a very significant impact;
- the number of hidden units is significant for the decision models (both with and without recurrence) but is not significant for the forecasting model;
- weight decay is never significant;
- higher-order interactions (of second and third order) between the factors are never significant.

2) Comparisons Between Models: In order to understand the performance differences attributable to the model type (decision with or without recurrence, forecasting), we performed pairwise comparisons between models.

Recall that for each model type, we have performance estimates for a total of 48 configurations (corresponding to the various settings of hidden units, of weight and input decay). One way to test for the impact of one model type over another would be to "align" the corresponding configurations of the two model types and perform paired t-tests on the generalization financial performance, and repeat this procedure for each of the 48 configurations. However, this method is biased because it does not account for the significant instantaneous cross-correlation in performance across configurations (in other words, the performance at time t of a model trained with weight decay set to 0.01 is likely to be quite similar to the same model type with weight decay set to 0.1, trained in otherwise the same conditions.[5])

Consider two model types to be compared, and denote their generalization financial returns $\{x_{it}\}$ and $\{y_{it}\}$ respectively. The index i denotes the configuration number (from 1 to $N = 48$ in our experiments), and t denotes the timestep (the number of generalization timesteps is $T = 187$ in our results). We wish

[4]This comparison is performed using a paired t-test to obtain reasonable-size confidence intervals on the differences. The basic assumptions of the t-test—normality and independence of the observations—were quite well fulfilled in our results.

[5]We have determined experimentally that the *autocorrelation* of returns (across time) is not statistically significant at any lag for any configuration of any model type; likewise, *cross-correlations* of returns across configurations are not statistically significant, except at lag 0. Hence, the procedure we describe here serves to account for these significant lag-0 cross-correlations.

TABLE I
ANOVA RESULTS FOR THE **decision model without recurrence**, SHOWING THE EFFECT OF SINGLE FACTORS (NUMBER OF HIDDEN UNITS (NH), WEIGHT DECAY (WD) AND INPUT DECAY (ID)) ALONG WITH SECOND- AND THIRD-ORDER INTERACTIONS BETWEEN THESE FACTORS. BOLD-STARRED ENTRIES ARE STATISTICALLY SIGNIFICANT AT THE 5% LEVEL. THE INPUT DECAY AND NUMBER OF HIDDEN UNITS FACTORS ARE SIGNIFICANT

	Degrees of freedom	Sum of squares	F-value	Pr(F)
ID	3	3.146	2.937	**0.032⋆**
WD	3	0.015	0.014	0.998
NH	2	3.458	4.841	**0.008⋆**
$ID:WD$	9	0.158	0.049	0.999
$ID:NH$	6	1.483	0.692	0.656
$WD:NH$	6	0.114	0.053	0.999
$ID:WD:NH$	18	0.589	0.092	0.999
Residuals	8928	3188.357		

TABLE II
ANOVA RESULTS FOR THE **decision model with recurrence**. THE SAME REMARKS AS TABLE I APPLY. THE INPUT DECAY AND NUMBER OF HIDDEN UNITS FACTORS ARE SIGNIFICANT

	Degrees of freedom	Sum of squares	F-value	Pr(F)
ID	3	8.482	8.649	**0.000⋆**
WD	3	0.111	0.114	0.952
NH	2	2.969	4.542	**0.012⋆**
$ID:WD$	9	0.392	0.133	0.999
$ID:NH$	6	1.505	0.767	0.596
$WD:NH$	6	0.286	0.146	0.990
$ID:WD:NH$	18	0.336	0.057	1.000
Residuals	8928	2918.357		

to test the hypothesis that $\overline{x} \neq \overline{y}$. To this end, we need an unbiased estimator of the variance of the sample mean difference. Let $e_{it} = x_{it} - y_{it}$ denote the sample differences. In order to perform the paired t-test, we wish to estimate

$$\text{Var}[\overline{e}] = \text{Var}\left[\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} e_{it}\right] \tag{66}$$

where $\overline{e}$ is the sample mean of e across all configurations and time steps

$$\overline{e} = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T} e_{it}. \tag{67}$$

The variance of $\overline{e}$, taking into account the covariance between e_{it} and e_{jt}, is given by

$$\text{Var}[\overline{e}] = \frac{1}{N^2T}\sum_{i=1}^{N}\text{Var}[e_i] + \frac{2}{N^2T}\sum_{i=1}^{N}\sum_{j=1}^{i-1}\text{Cov}[e_i, e_j]. \tag{68}$$

This equation relies on the following assumptions: 1) the variance of the e_{it} within a given configuration i is stationary (time invariant), which we denote by $\text{Var}[e_i]$; 2) the covariance between e_{it} and e_{jt}, for $i \neq j$, is also stationary (denoted above by $\text{Cov}[e_i, e_j]$); 3) the covariance between e_{it_1} and e_{jt_2}, for $t_1 \neq t_2$, and all i, j, is zero. As mentioned above, we have verified experimentally that these assumptions are indeed very well satisfied.

TABLE III
ANOVA RESULTS FOR THE **forecasting model without recurrence**. THE SAME REMARKS AS TABLE I APPLY. THE INPUT DECAY FACTOR IS SIGNIFICANT

	Degrees of freedom	Sum of squares	F-value	Pr(F)
ID	3	5.483	3.617	**0.013⋆**
WD	3	0.068	0.044	0.988
NH	2	0.384	0.380	0.684
$ID:WD$	9	0.172	0.038	1.000
$ID:NH$	6	3.684	1.215	0.295
$WD:NH$	6	0.207	0.068	0.999
$ID:WD:NH$	18	0.977	0.107	1.000
Residuals	8928	4511.072		

TABLE IV
PAIRWISE COMPARISONS BETWEEN ALL MODEL TYPES: THE CHOICE OF MODEL TYPE DOES NOT HAVE A STATISTICALLY SIGNIFICANT IMPACT ON PERFORMANCE. THE TEST IS PERFORMED USING THE CROSS-CORRELATION-CORRECTED t-TEST DESCRIBED IN THE TEXT; 'D' STANDS FOR THE DECISION MODEL, AND 'F' FOR THE FORECASTING MODEL

Model x	Model y	Sample $x-y$	t-value	Pr(t)
D. w/ recur.	D. w/o recur.	0.002	0.144	0.886
F. w/o recur.	D. w/o recur.	0.027	0.874	0.382
F. w/o recur.	D. w/o recur.	0.025	0.821	0.412

The variances $\text{Var}[e_i]$ and covariances $\text{Cov}[e_i, e_j]$ can be estimated from the financial returns at all time steps within configurations i and j.

Finally, to test the hypothesis that the performance difference between model types x and y is different from zero, we compute the t statistic

$$t = \frac{\overline{e}}{\sqrt{\widehat{\text{Var}}[\overline{e}]}} \tag{69}$$

where $\widehat{\text{Var}}[\overline{e}]$ is an estimator of $\text{Var}[\overline{e}]$ computed from estimators of $\text{Var}[e_i]$ and $\text{Cov}[e_i, e_j]$.

Our results for the pairwise comparisons between all model types appear in Table IV. We observe that the p-values for the differences between model types is never statistically significant, and from these results, we cannot draw definitive conclusions as to the relative merits of one model type over another.

C. Results with Model Combination

We now turn to the investigation of model combination methods. The raw results obtained by the combination methods are given in Tables I–VII, respectively for the decision models without and with recurrence, and the forecasting model. Each table gives the generalization financial performance obtained by a committee constructed by combining MLPs with the same number of hidden units, but trained with different values of the hyperparameters controlling weight decay and input decay (all combinations of $\phi_{\mathsf{WD}} \in \{10^{-3}, 10^{-2}, 10^{-1}, 10^{0}\}$ and $\phi_{\mathsf{ID}} \in \{10^{-3}, 10^{-2}, 10^{-1}, 10^{0}\}$.) Each result is given with a standard error derived from the t distribution, along with the difference in performance with respect to the market benchmark (whose standard error is derived from the t distribution using paired differences.)

A graph summarizing the results for the exponentiated gradient combination method appears in Fig. 8. Similar graphs are obtained for the other combination methods.

TABLE V
RESULTS FOR THREE MODEL COMBINATION METHODS, APPLIED TO THE **decision model without recurrence**. NH REFERS TO THE NUMBER OF HIDDEN UNITS. THE AVERAGE NET MARKET RETURN FOR THE PERIOD UNDER CONSIDERATION IS 0.009 (STANDARD ERROR = 0.042). BOLD-STARRED ENTRIES ARE STATISTICALLY SIGNIFICANT AT THE 5% LEVEL

	Exponentiated Gradient				Softmax				Hardmax			
NH	Avg. Return		Diff. w/ market		Avg. Return		Diff. w/ market		Avg. Return		Diff. w/ market	
2	0.023	(0.044)	0.014	(0.035)	0.043	(0.043)	0.034	(0.033)	0.012	(0.045)	0.003	(0.059)
5	**0.107**	**(0.041)** ⋆	0.099	(0.056)	**0.099**	**(0.041)** ⋆	0.090	(0.053)	**0.126**	**(0.041)** ⋆	0.117	(0.061)
10	**0.090**	**(0.045)** ⋆	0.081	(0.060)	**0.089**	**(0.045)** ⋆	0.080	(0.060)	0.083	(0.046)	0.074	(0.057)

TABLE VI
RESULTS FOR THREE MODEL COMBINATION METHODS, APPLIED TO THE **decision model with recurrence**. THE SAME REMARKS AS IN TABLE V APPLY. MANY OF THOSE COMMITTEES SIGNIFICANTLY BEAT THE MARKET

	Exponentiated Gradient				Softmax				Hardmax			
NH	Avg. Return		Diff. w/ market		Avg. Return		Diff. w/ market		Avg. Return		Diff. w/ market	
2	0.072	(0.043)	0.063	(0.038)	**0.087**	**(0.042)** ⋆	**0.078**	**(0.036)** ⋆	0.050	(0.039)	0.041	(0.052)
5	**0.138**	**(0.041)** ⋆	**0.129**	**(0.051)** ⋆	**0.132**	**(0.041)** ⋆	**0.123**	**(0.047)** ⋆	**0.124**	**(0.041)** ⋆	**0.116**	**(0.054)** ⋆
10	**0.090**	**(0.042)** ⋆	0.081	(0.056)	**0.084**	**(0.043)** ⋆	0.076	(0.056)	**0.106**	**(0.042)** ⋆	0.097	(0.057)

TABLE VII
RESULTS FOR THREE MODEL COMBINATION METHODS, APPLIED TO THE **forecasting model without recurrence**. THE SAME REMARKS AS IN TABLE V APPLY. MANY OF THOSE COMMITTEES SIGNIFICANTLY BEAT THE MARKET

	Exponentiated Gradient				Softmax				Hardmax			
NH	Avg. Return		Diff. w/ market		Avg. Return		Diff. w/ market		Avg. Return		Diff. w/ market	
2	**0.127**	**(0.052)** ⋆	**0.119**	**(0.048)** ⋆	**0.137**	**(0.052)** ⋆	**0.128**	**(0.049)** ⋆	0.031	(0.050)	0.022	(0.048)
5	**0.156**	**(0.055)** ⋆	**0.147**	**(0.053)** ⋆	**0.138**	**(0.053)** ⋆	**0.129**	**(0.054)** ⋆	**0.130**	**(0.054)** ⋆	**0.121**	**(0.050)** ⋆
10	**0.113**	**(0.052)** ⋆	0.104	(0.058)	**0.120**	**(0.051)** ⋆	0.111	(0.057)	0.040	(0.052)	0.032	(0.058)

By way of illustration, Fig. 9 shows the (out-of-sample) behavior of one of the committees. The top part of the figure plots the monthly positions taken in each of the 14 assets. The middle part plots the monthly returns generated by the committee and, for comparison, by the market benchmark; the monthly value-at-risk, set in all our experiments to 1$, is also illustrated, as an experimental indication that is is not traversed too often (the monthly return of either the committee or the market should not go below the $-1$$ mark more than 5% of the times). Finally, the bottom part gives the net cumulative returns yielded by the committee and the market benchmark.

This figure illustrates an important point: the positions taken in each asset by the models (top) are by no means "trivial": they vary substantially with time, they are allowed to become fairly large in magnitude (both positive and negative), and yet, even after accounting for transaction costs, the target VaR of $1 is reached and the trading model is profitable.

1) ANOVA Results for Committees: Tables VIII and IX formally analyze the impact of the model combination methods.

Restricting ourselves to the exponentiated gradient committees, we first note (Table VIII) that *no factor*, either the model type or the number of hidden units, has a statistically significant effect on the performance of the committees.

Secondly, when we contrast all the combination methods taken together, we note that the number of hidden units has an overall significant effect. This appears to be attributable to the relative weakness of the "hardmax" combination method, even though no direct statistical evidence can confirm this conjecture. The other combination methods—softmax and exponentiated gradient—are found to be statistically equivalent in our results.

TABLE VIII
ANOVA RESULTS FOR THE EXPONENTIATED GRADIENT COMMITTEES. THE FACTORS ARE THE MODEL TYPE (NOTED M: DECISION WITHOUT OR WITH RECURRENCE; FORECASTING) AND THE NUMBER OF HIDDEN UNITS (NOTED NH), ALONG WITH THE INTERACTION BETWEEN THE TWO. NO FACTOR CAN BE SINGLED OUT AS "THE MOST IMPORTANT"

	DoF	Sum of squares	F-value	Pr(F)
M	2	0.959	1.215	0.297
NH	2	1.006	1.274	0.280
$M:NH$	4	0.346	0.219	0.928
Residuals	1665	657.217		

2) Comparing a Committee with its Underlying Models: We now compare the models formed by the committees (restricting ourselves to the exponentiated gradient combination method) against the performance of their *best underlying* model, and the *average performance* of their underlying models, for all model types and number of hidden units.

Table X indicates which of the respective underlying models yielded the best performance (*ex post*) for each committee, and tabulates the average difference between the performance of the committee (noted x) and the performance of that best underlying (noted y). Even though a committee suffers in general

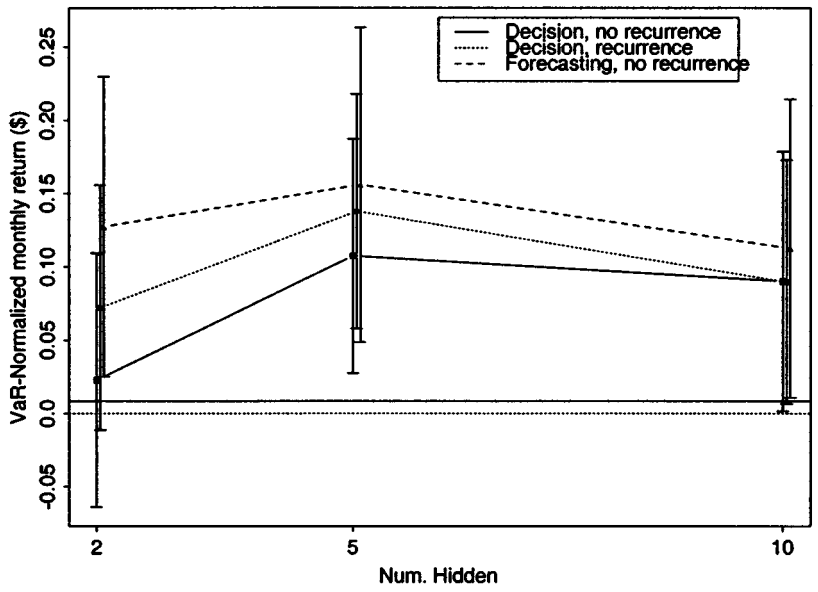

Fig. 8. Out-of-sample performance of committees (made with exponentiated gradient) for three types of models. The market performance is the solid horizontal line just above zero. The error bars denote 95% confidence intervals. We note that the forecasting committee is slightly but not significantly better than the others.

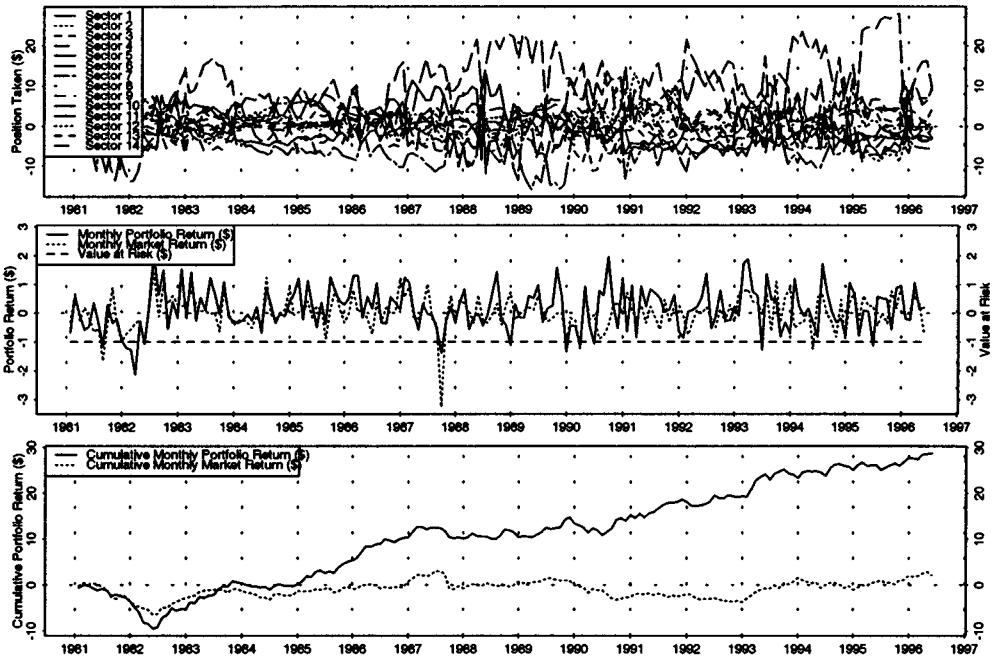

Fig. 9. Out-of-sample behavior of the (exponentiated gradient) committee built upon the forecasting model with five hidden units. (a) Monthly positions (in $) taken in each asset. (b) Monthly return, along with the 95%-VaR (set to 1$); we note that the risks taken are approximately as expected, from the small number of crossings of the $-1$$ horizontal line. (c) Cumulative return: the decisions would have been very profitable. Note that the positions taken in (a) vary substantially and are allowed to become fairly large in magnitude, and yet the target VaR is maintained and the model is profitable.

from a slight performance degradation with respect to its best underlying model, this difference is, in no circumstance, statistically significant. (Furthermore, we note that the best underlying model can never directly be used by itself, since its performance can only be evaluated after the facts.)

Table XI gives the results of the average performance of the underlying models (noted y) and compares it with the performance of the committee itself (noted x). We note that the committee performance is significantly better in four cases out of nine, and "quasisignificantly" better in two other cases. We observe that comparing a committee to the average performance of its underlying models is equivalent to randomly picking one of the underlyings.

We can conclude from these results that, contrarily to their human equivalents, model committees can be significantly more intelligent than one of their members picked randomly, and can never be (according to our results) significantly worse than the *best* of their members.

3) Is the Target VaR Really Reached?: Finally, a legitimate question to ask is whether the target value at risk is indeed

TABLE IX
ANOVA RESULTS COMPARING THE MODEL COMBINATION METHOD (NOTED C: HARDMAX; SOFTMAX; EXP. GRADIENT), THE MODEL TYPE (NOTED M, AS BEFORE), THE NUMBER OF HIDDEN UNITS (NOTED NH), ALONG WITH HIGHER-ORDER INTERACTIONS BETWEEN THESE FACTORS. THE NUMBER OF HIDDEN UNITS IS THE ONLY SIGNIFICANT FACTOR

	DoF	Sum of squares	F-value	Pr(F)	
C	2	0.673	0.862	0.422	
M	2	1.094	1.401	0.246	
NH	2	3.365	4.309	**0.013**	⋆
$C:M$	4	0.905	0.579	0.678	
$C:NH$	4	0.546	0.350	0.844	
$M:NH$	4	0.674	0.431	0.786	
$C:M:NH$	8	0.302	0.097	0.999	
Residuals	4995	1950.545			

TABLE X
ANALYSIS OF THE PERFORMANCE DIFFERENCE BETWEEN THE EXPONENTIATED GRADIENT COMMITTEES AND THE BEST UNDERLYING MODEL THAT IS PART OF EACH COMMITTEE. WE OBSERVE THAT THE COMMITTEES ARE NEVER SIGNIFICANTLY WORSE THAN THE BEST MODEL THEY CONTAIN

Model		Underlying $\langle WD, ID\rangle$	Perf. difference	t-value	DoF	p-valu
Decision w/o recur.	NH=2	10^{-1}, 10^{-1}	−0.034	−0.77	185	0.43
	NH=5	10^{0} , 10^{-3}	−0.033	−1.65	185	0.10
	NH=10	10^{-3}, 10^{-1}	−0.019	−0.82	185	0.41
Decision w/ recur.	NH=2	10^{0} , 10^{-3}	−0.024	−0.71	185	0.47
	NH=5	10^{-3}, 10^{-2}	−0.001	−0.05	185	0.95
	NH=10	10^{-3}, 10^{-3}	−0.024	−1.59	185	0.11
Forecast w/o recur.	NH=2	10^{-2}, 10^{-3}	0.005	0.16	185	0.86
	NH=5	10^{-2}, 10^{-1}	−0.007	−0.22	185	0.82
	NH=10	10^{-3}, 10^{-1}	−0.015	−0.46	185	0.64

TABLE XI
ANALYSIS OF THE PERFORMANCE DIFFERENCE BETWEEN THE EXPONENTIATED GRADIENT COMMITTEES AND THE ARITHMETIC MEAN OF THE PERFORMANCE OF THE MODELS THAT ARE PART OF EACH COMMITTEE (EQUIVALENT TO AVERAGE PERFORMANCE OBTAINED BY RANDOMLY PICKING A MODEL FROM THE COMMITTEE). FOR THE DECISION MODEL WITH RECURRENCE AND THE FORECASTING MODEL, WE SEE THAT THE COMMITTEES FREQUENTLY SIGNIFICANTLY OUTPERFORM THE RANDOM CHOICE OF ONE OF THEIR MEMBERS

Model		Average of underlyings	Perf. Difference	t-value	DoF	p-value	
Decision w/o recur.	NH=2	0.033 (0.033)	−0.012	−0.539	185	0.591	
	NH=5	0.078 (0.034)	0.026	1.595	185	0.112	
	NH=10	0.070 (0.040)	0.016	1.834	185	0.068	
Decision w/ recur.	NH=2	0.043 (0.030)	0.025	1.106	185	0.270	
	NH=5	0.087 (0.032)	0.049	3.156	185	**0.002**	⋆
	NH=10	0.057 (0.039)	0.032	2.653	185	**0.009**	⋆
Forecast w/o recur.	NH=2	0.095 (0.042)	0.030	2.008	185	**0.046**	⋆
	NH=5	0.089 (0.040)	0.065	3.471	185	**0.001**	⋆
	NH=10	0.079 (0.040)	0.031	1.902	185	0.059	

reached by the models. This is an important question for ensuring that the incurred risk exposure is comparable to that chosen by the portfolio manager.

Our approach to carry out this test is to construct confidence intervals around the fifth percentile (since we ran our experiments at 95%-level VaR) of the empirical returns distribution of the *committee models*. We want to ensure that the confidence intervals include the $–1 mark, which is our target VaR.

TABLE XII
95% CONFIDENCE INTERVALS FOR THE 5TH PERCENTILE OF THE RETURNS DISTRIBUTION FOR COMMITTEES OF VARIOUS ARCHITECTURES (COMBINED USING THE SOFTMAX METHOD). WE NOTE THAT ALL THE CONFIDENCE INTERVALS INCLUDE THE $–1 POINT, WHICH WAS THE TARGET VALUE-AT-RISK IN THE EXPERIMENTS. WE ALSO OBSERVE THAT THE ASYMPTOTIC AND BOOTSTRAP INTERVALS ARE QUITE SIMILAR. NH REFERS TO THE NUMBER OF HIDDEN UNITS

Architecture	NH	Bootstrap	Asymptotic
Decision without Recurrence	2	(−0.72, −1.28)	(−0.74, −1.31)
	5	(−0.62, −1.02)	(−0.65, −1.14)
	10	(−0.63, −1.30)	(−0.70, −1.42)
Decision with Recurrence	2	(−0.58, −1.07)	(−0.64, −1.26)
	5	(−0.52, −1.02)	(−0.53, −1.19)
	10	(−0.63, −1.15)	(−0.64, −1.33)
Forecasting without Recurrence	2	(−0.72, −1.26)	(−0.80, −1.42)
	5	(−0.81, −1.23)	(−0.83, −1.26)
	10	(−0.76, −1.14)	(−0.78, −1.39)

We consider two manners of constructing said confidence intervals, the first based on an asymptotic result, and the second based on the bootstrap.

c) Asymptotic Confidence Intervals: Let $\tilde{Q}(u)$ be the empirical quantile function in a random sample $\{X_j\}$ of size n

$$\tilde{Q}(u) = X_{j:n}, \quad \frac{j-1}{n} < u \leq \frac{j}{n}, \qquad j = 1, \cdots, n$$

where $X_{j:n}$ denotes the jth order statistic of the random sample. Then, it is well known (e.g., [24]) that an asymptotic $100(1-\alpha)\%$ confidence interval for the population quantile $Q(p)$, $0 < p < 1$, is given by

$$(\tilde{Q}(k_1/n), \tilde{Q}(k_2/n)) \tag{70}$$

where k_1 and k_2 are integers chosen so that

$$k_1 \approx np - \Phi^{-1}(\alpha/2)\sqrt{np(1-p)} \tag{71}$$

and

$$k_2 \approx np + \Phi^{-1}(\alpha/2)\sqrt{np(1-p)} \tag{72}$$

with $\Phi^{-}1(\cdot)$ the inverse cumulative function of the standard normal distribution.

d) Bootstrap Confidence Intervals: The bootstrap confidence intervals are found simply from the bootstrap sampling distribution of the qth quantile statistic. More specifically, we resample (with replacement) the empirical returns of a model a large number of times (5000 in our experiments), and compute the position of qth quantile in each sample. The $100(1-\alpha)\%$ confidence intervals are given by the location of the $\alpha/2$ and $1-\alpha/2$ quantiles of the bootstrap distribution.

e) Confidence Intervals Results: We computed confidence intervals at the 95% level for committees of the various architectures. Results for the softmax combination method appear in Table XII. The results obtained for the other combination methods are quite alike, and are omitted for brevety. We observe that all the confidence intervals in the table include the

$–1 point, from which we conclude that we cannot reject the null hypothesis that the target value at risk is not reached.

VI. Conclusion

We demonstrated the success of directly training a (possibly recurrent) neural network according to a VaR-adjusted profit criterion for making asset-allocation decisions within a VaR-control framework. The performance results are comparable to those obtained with a forecasting model used jointly with classical mean-variance portfolio selection. Both the forecasting and decision models perform significantly better than the benchmark market performance.

Recall that the decision model can be preferred to the forecasting model since it relies on fewer assumptions with respect to the workings of the investment process. In particular, the decision model does not need to postulate that investors are driven by a utility function of a specific analytical form; instead, the model is trained to directly optimize the financial criterion of interest. Furthermore, the recurrent network topology we used makes it possible to account for transaction costs to a certain extent.

We showed how a recurrent neural network can be trained to directly optimize a risk-constrained profit criterion, which ensures that *the value-at-risk constraint on the portfolio remains satisfied*, and that correctly accounts for transaction costs. We further showed the importance of a "reference norm" or "reference portfolio" regularizer to make the optimization problem well-posed and numerically well-behaved.

In addition, we showed the importance of the input decay regularizer as a soft input selection procedure, in the case where networks contain a large number of inputs.

Finally, we noted an effective use of committee methods to systematize the choice of hyperparameters during neural network training. While many of their underlying models are underperformers, we found that several of our committees (both of the forecasting and the decision types) are nevertheless significantly outperforming the benchmark market index.

Future work includes improving explanatory variables, such as incorporating more thorough volatility modeling, as well as taking full advantage of the recurrent structure of the neural network by making use of hidden states.

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