Is this Time Different? Financial Follies across Centuries*

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Abstract

Carmen Reinhart and Ken Rogoff have written that "no matter how different the latest financial frenzy or crisis always appears, there are usually remarkable similarities with past experience from other countries and from history". Can we really use the same models to predict the 20th century Great Depression and the 21st century Great Recession? We find that based exclusively on models estimated on the period 1874-1922, we can predict out-of-sample the 1929 Great Depression and all the 20th and 21st century systemic financial crises.

Keywords: Financial crises, early warning indicators, financial history

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1 Introduction

Eichengreen and Portes (1987) write that "much as the study of disease is one of the most effective ways to learn about human biology, the study of financial crises provides one of the most revealing perspectives on the functioning of monetary economies." Crises can be defined as strong disturbances to financial markets, accompanied by sharp falls in asset prices and widespread insolvencies among debtors and intermediaries, which disrupts the capacity to allocate capital within the economy and leads to a decrease in real activity. As shown in the classic Reinhart and Rogoff (2009) book "This Time is Different, Eight hundred years of Financial Follies", financial crises have occurred repeatedly in emerging markets and advanced economies alike, and they exhibit some remarkable similarities. Crises are often, but not always, credit booms gone bust as described by Minsky (1986) and Kindleberger (1978). As the Great Depression unfolds, Fisher (1933) states that "over-investment and over-speculation are often important; but they would have far less serious results were they not conducted with borrowed money. That is, over-indebtedness may lend importance to over-investment or to over-speculation. The same is true as to over-confidence. I fancy that over-confidence seldom does any great harm except when, as, and if, it beguiles its victims into debt." From a theoretical point of view, there are many different models in macroeconomics and in finance which have been developed to understand the causes and mechanics of crises. Some emphasise runs as in Diamond and Dybvig (1983). Many models in macro-finance focus on the bust phase of the crisis and on amplification mechanisms such as fire sales of assets. A few analyze the boom phase of the financial cycle and emphasise limited liability and asset overvaluations due to risk-shifting (Coimbra and Rey (2017)), search-for-yield in low interest rates environments (Martinez-Miera and Repullo (2017)), or deviations from rational expectations and financial constraints (Gennaioli et al. (2012)). From an empirical point of view, a number of variables have been used to predict financial crises -mostly in-sample. Following Kaminski and Reinhart (1999), the literature has very usefully described the behaviour of a number of key variables around crisis episodes (see e.g. Gourinchas and Obstfeld (2012)). Lowe and Borio (2002) and Schularick and Taylor (2012) emphasise further the role of credit growth and Mian and Sufi (2009) underlines the importance of household debt in the making of severe financial crises. But are the similarities between crises large enough to make them predictable? Can we take Reinhart and Rogoff (2009) literally and use information from the end of the 19th and the very beginning of the 20th century to predict the Great Depression and all subsequent systemic crises in a panel of countries? The answer provided by this paper is largely positive. Based exclusively on models estimated on the period 1896-1922, we can predict out-of-sample the 1929 Great Depression and all the 20th

and 21st century systemic crises three years ahead.

The paper is structured as follows. In section 2 we introduce and discuss the online learning methodology, which forms the basis of our predictive strategy. In section 3, we present our data and a set of empirical models of financial crises. Results and their interpretation are in section 4. Section 5 concludes.

2 Sequential learning about crises over a hundred years

Most of the literature on crises uses standard econometric methods such as panel data analysis or event studies in order to identify early warning indicators of financial crises. Some recent attempts to introduce new forecasting methods imported from the machine learning literature can be found in Ward (2017) who uses classification trees and Bluwstein et al. (2020) who compare the forecasting performance of decision trees, random forests, extremely randomised trees, support vector machines, and artificial neural networks. Instead, we adopt the *framework of sequential prediction or online machine learning* (see Cesa-Bianchi and Lugosi (2006)), which aggregates optimally a large number of models. As such it is more general, since if any model has a superior forecasting power, it will get picked, but if some models perform better at different points in time, the methodology will increase or decrease their weights in the forecast accordingly. Furthermore, unlike in the classical statistical theory of sequential predictions, where the sequence of outcomes is assumed to be a realization of a stationary stochastic process, in our framework, crises are the product of some unknown and unspecified mechanism, which could be deterministic, stochastic, or even adversarially adaptative to our own behavior. This allows us to make no assumptions on how the data are generated, which is a big advantage as there is no consensus on a theory of financial crises. Online machine learning is specifically geared at real-time prediction in situations where the true models driving outcomes are not known and can be different over time. We aim at predicting pre-crises (3 year before a crisis) since this is the relevant horizon for macro prudential policies aiming at fostering financial stability. Our approach can be described as "meta-statistic" since the aim is to make the best prediction by aggregating models (also called experts)' predictions. The forecaster's error is then the sum of two errors : an *estimation error* measured by the error of the best combination of experts, known *ex post*, representing the best prediction the forecaster can make using the available information and an *approximation error* measuring the difficulty to approach *ex ante* the best combination of experts. Though based on model averaging with time varying weights, *on-line learning* is

more general than Bayesian Model Averaging[1]; importantly and as already mentioned, it does not make any assumption on the data generating processes; furthermore it allows for time-varying learning rates. To our knowledge, there are only two papers applying online machine learning to economics: Amat et al. (2018) for models of exchange rates and our own work on post 1980 crises in Europe on a rich set of quarterly macro-financial variables (Fouliard et al. (2020)). In contrast online learning has been used in a number of applications outside economics, for example to forecast electricity consumption (Devaine et al. (2013)), to track the performance of climate models (Monteleoni et al. (2011)), to model the network traffic demand (Dashevskiy and Luo (2011)), to forecast air quality (Mallet et al. (2009)) and to predict of outcomes of sports games Dani et al. (2012). An advantage of the methodology is that it also allows us to track which models perform well over time in a given country. This is an important characteristic which sets it apart from "data mining" or black box approaches. This is often enlightening to understand sources of instability -though of course we cannot formally identify any *causal relationship* between variables having good forecasting power and the origins of the crisis.

2.1 Online Learning Methodology

Consider a bounded sequence of observations (the occurence or non-occurrence of pre-crisis periods) $y_1, y_2, ..., y_T$ in an outcome space $\mathcal{Y}$. The goal of the forecaster is to make the predictions $\hat{y_1}, \hat{y_2}, ..., \hat{y_T}$ in a decision space $\mathcal{D}$.

This framework has two main specificities. First, the observations $y_1, y_2, ...,$ are revealed in a sequential order. At each step $t = 1, 2, ..$, the forecaster makes a prediction $\hat{y_t}$ on the basis of the previous $t-1$ observations before the tth observation is revealed. This is why this approach is said to be "online" since the forecaster sequentially receives information. The optimal forecasting model is adaptable over time which is very convenient when the predictive content is unstable over time. This lack of stability is indeed a stylized fact in the forecasting literature (Stock and Watson (2012) and Rossi (2011)). In contrast to the stochastic modelling approach, we do not assume that $y_1, y_2, ...$ are the product of a stationary stochastic process. The sequence $y_1, y_2, ...$ could be the result of the interactions of very complex non linear processes.

The forecaster predicts the sequence $y_1, y_2, ...$ using a set of "experts". Experts are predictive models. They can be statistical models, an opinion on y_t using private sources of in-

[1] In some cases, even very simple ones (see Grunwald and van Ommen (2014)), Bayesian Model averaging does not converge due to heteroskedasticity.

formation or a black box of unknown computational power (neural networks for example). Each expert $j = 1, ..., N \in \mathcal{E}$ makes the prediction $f_{j,t}$ based only on information available until date t-1. The methodology of *online learning* is therefore extremely flexible and general as any forecasting model can be used to contribute to the optimal forecast. But of course there is no magic, if all forecasting models are bad, the optimal forecast will also be bad. If we put "garbage in", we will get "garbage out".

To combine experts' advice, the forecaster chooses a sequential aggregation rule $\mathcal{S}$ which consists in picking a time-varying weight vector $(p_{1,t}, ..., p_{N,t}) \in \mathcal{P}$. The forecaster's outcome is the linear combination of experts' advice :

$$\hat{y_t} = \sum_{j=0}^{N} p_{j,t} f_{j,t}$$

After having computed $\hat{y_t}$ (based on information available until t-1), the forecaster and each expert incur a loss defined by a non-negative loss function : $\ell : \mathcal{D} \times \mathcal{Y}$.

How do we measure the sequential aggregation rule's performance ? If the sequence $y_1, y_2, ...$ were the realisation of a stationary stochastic process, it would be possible to estimate the performance of a prediction strategy by measuring the difference between predicted value and true outcome. But we do not have any idea about the generating process of the observations. However, one possibility is to compare the forecaster's strategy with the best expert advice. Let's define the difference between the forecaster's loss and the loss of a given expert, cumulated over time:

$$R_{j,T} = \sum_{t=1}^{T} (\ell(\hat{y_t}, y_t) - \ell(f_{j,t}, y_t)) = \hat{L_T} - L_{j,T}$$

where $\hat{L_T} = \sum_{t=1}^{T} \ell(\hat{y_t}, y_t)$ denotes the forecaster's cumulative loss and $L_{j,T} = \sum_{t=1}^{T} \ell(f_{j,t}, y_t)$ is the cumulative loss of the expert j.

The *regret* of a sequential aggregation rule $\mathcal{S}$ is given by :

$$R(\mathcal{S}) = \hat{L}_T(\mathcal{S}) - \inf_{q \in \mathcal{P}} L_T(q)$$

where $\inf_{q \in \mathcal{P}} L_T(q) = \inf_{q \in \mathcal{P}} \sum_{t=1}^{T} \ell(\sum_{j=0}^{N} q_{j,t} f_{j,t}, y_t)$ is the cumulative loss of the best convex combination of experts (known *ex post*).

This difference is called "regret" since it measures how much the forecaster regrets not having followed the advice of this particular combination of experts. The regret is a way of measuring the performance of a forecaster's strategy by comparing the forecaster's predictions (based on information at date t-1) with the best prediction which could have been done had she followed a certain combination of experts based on realised value at date t.

Knowing that $\hat{y}_t = \sum_{j=0}^{N} p_{j,t} f_{j,t}$, the regret can be written as :

$$R(\mathcal{S}) = \sum_{t=1}^{T} \ell(\sum_{j=1}^{N} p_{j,t} f_{j,t}, y_t) - \inf_{q \in \mathcal{P}} \sum_{t=1}^{T} \ell(\sum_{j=1}^{N} q_{j,t} f_{j,t}, y_t)$$

Minimizing the regret is for the forecaster a robustness requirement. When the regret is close to 0, it ensures that forecaster's strategy (determined at date t-1) is close to the best combination of experts, which is known at the end of the round (at date t). To get a robust aggregation rule, the forecaster wants, in addition of having the smallest bound possible for the regret, to obtain a "vanishing per-round regret" so that when T goes to infinity the superior limit of the regret taken over all possible observation and prediction sequences goes to zero:

$$\lim_{T \to \infty} \sup \left\{ \frac{R(\mathcal{S})}{T} \right\} \leq 0$$

In this case, the forecaster's cumulative loss will converge to the loss of the best linear combination of experts known *ex-post*. This approach can be described as "meta-statistic" since the aim is to find the best sequential linear combination of experts. Indeed, the following decomposition:

$$\hat{L}_T(\mathcal{S}) = \inf_{q \in \mathcal{P}} L_T(q) + R(\mathcal{S})$$

indicates that the forecaster's cumulative loss is the sum of an estimation error, given by the cumulative loss of the best linear combination of experts (known *ex post*), and by the regret which measures the difficulty to approach *ex ante* the best combination of experts[2]. In our case we also have to take into account the delayed informational feedback as we know if we are in a pre-crisis period only 3 years later (when the crisis starts) so we update our weights

[2]The bound of the regret guarantees that forecasters performance will compete with the performance of the best convex combination of experts when T goes to ∞. The forecaster's strategy is often worse than the performance of the best convex combination of experts since the best convex combination is known *ex post*, but it is not a theoretical necessity. With time-varying weights, an excellent online strategy could be able to beat the best (fixed) convex combination of experts.

of the aggregation rule with a 3 year delay. We describe the algorithm used in more details in Appendix.

2.2 Loss function

The loss function can take different forms. The only constraint is that it should be convex and bounded for minimizing the regret. In our case, we are seeking to predict a binary outcome so there is no issue. We use a squared loss function $\ell(\hat{y}_t, y_t) = (\hat{y}_t - y_t)^2$ (but could also use an absolute loss function $\ell(\hat{y}_t, y_t) = |\hat{y}_t - y_t)|$). Which of them is more appropriate for a given problem is an empirical question though the squared loss function tends to have better out-of-sample performance.

2.3 Time Varying Aggregation Weights

We use the Exponentially weighted average aggregation rule. This convex aggregation rules combine experts' predictions with a time-varying vector $p_t = (p_{1,t}, ..., p_{N,t})$ in a simplex $\mathcal{P}$ of $\mathbb{R}^N$:

$$\forall j \in \{1, ..., N\}, p_{j,t} \geq 0 \text{ et } \sum_{k=1}^{N} p_{k,t} = 1$$

We use the exponentially weighted average (EWA) aggregation rule as it presents key advantages. First, the weights are computable in a simple incremental way. Second, the forecaster's predicted probability only depends on the past performance of the experts and not on his past prediction. The forecaster predicts at each time t :

$$\hat{y}_t = \frac{\sum_{j=1}^{N} e^{-\eta_t L_{j,t-1}} f_{j,t}}{\sum_{i=1}^{N} e^{-\eta_t L_{i,t-1}}}$$

where η_t is the learning rate, the speed at which weights are updated.

We use the gradient-based version of the EWA aggregation rule $\mathcal{E}_\eta^{\text{grad}}$ where weights are defined by :

$$p_{j,t} = \frac{\exp(-\eta_t \sum_{s=1}^{t-1} \tilde{L_{j,s}})}{\sum_{k=1}^{N} \exp(-\eta_t \sum_{s=1}^{t-1} \tilde{L_{k,s}})}$$

where $\tilde{L_{j,s}} = \nabla \ell(\sum_{k=1}^{N} p_{k,s} f_{k,s}, y_s) \cdot f_{j,s}$ and ∇ is the gradient operator.

An important advantage of the gradient-based version of the EWA aggregation rule is that weights are easy to interpret. If expert j's advice $f_{j,s}$ points in the direction of the largest

increase of the loss function, i.e. if the inner products $\nabla\ell(\sum_{k=1}^{N} p_{k,s} f_{k,s}, y_s) \cdot f_{j,s}$ has been large in the past, the weight assigned to expert j will be small. The learning rate is optimised empirically. The algorithm is described in more detail in Appendix.

3 Data on Macro-History and Models of Crises

We use the macro-history data set of Jordà et al. (2017) and Jordà et al. (2019) which covers the period 1870-2016 for Australia, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, UK and the US. The data are annual. Given our application which requires our algorithm to learn at the beginning of the sample we can only use a limited set of variables as we cannot incorporate those with missing values. We are therefore left with variables describing real economic activity such as Real GDP per capita, GDP, Consumer prices, Investment-to-GDP ratio, government expenditure; monetary aggregates: Broad money, Narrow money; lending and borrowing variables: loans, mortgages, Debt-to-GDP; asset prices: short-term interest rate, long-term interest rate, stock prices, house prices; the external sector: exports, current account, imports, exchange rate. We also use the crisis variables of the data set and have therefore a total of eighteen variables.

To predict the 1929 crisis, our methodology requires two other crises before: a first one because the experts have to be estimated on a batch sample, a second one for the aggregation rule to learn on a crisis in a sequential way. We therefore focus on countries which satisfy two criteria : i) it has two crises before 1929 ii) there is enough data so that it is possible to compute each expert.

In our database, seven countries satisfy this requirement: France, Germany, Japan, Netherlands, Spain and the United States. The batch samples, i.e. the samples on which the learning takes place are indicated in Table 1. They start in 1896 due to data availability and end as early as 1906 for the US or as late as 1922 for Italy depending on the timing of 19th century or early 20th century crises. From 1922 at the latest, we predict financial crises out-of-sample three years ahead for all the seven countries.

3.1 Models of crises (experts)

We use two kinds of experts: elastic-net logits and machine learning experts.

Country	Batch sample	Online sample
United States	1874 - 1906	1906 - 2017
France	1880 - 1920	1920 - 2017
Italy	1880 - 1922	1922 - 2017
Japan	1880 - 1918	1918 - 2017
Spain	1880 - 1921	1921 - 2017
Netherlands	1880 - 1914	1914 - 2017
Portugal	1880 - 1907	1907 - 2017

Table 1: Batch and Online Samples

3.1.1 Elastic-net logits Experts

Elastic-net logits are a regularized regression method that combines linearly the penalties of the LASSO and the Ridge with certain weights[3]. They have been found to be particularly well-suited for out-of-sample forecasts. First introduced by Zou and Hastie (2005), the good performance of elastic-net penalty compared to other regularization methods has been confirmed in various applications (Mol et al. (2009a); Mol et al. (2009b); Destrero et al. (2009))[4]. We design the elastic-net logits by grouping variables by themes in order to ease the economic interpretation of our results. Two logits describe the real economy (**lre**: Real GDP per capita, GDP, Consumer prices and **lre2**: GDP, Investment-to-GDP ratio, Consumer prices, Exports); another one is about valuations (**lval** : Short-term interest rate, Long-term interest rate, Stock prices, House prices); another is about the foreign sector (**lfor** : Current account, Imports, Exports). These four logits are common to all the countries. We also introduce elastic net logit combinations which are specific for each country. The variables included are the ones which have the highest AUROCs (Area Under the Receiving Operator Curve) on the batch sample, following Schularick and Taylor (2012) and Coudert and Idier (2016). The ROC curve represents the ability of a binary classifier by plotting the true positive rate against the false positive rate for all thresholds. The closer to one an AUROC is, the more accurate the classification is. For each country we have four combination logits. Their variables for each country are detailed in the Appendix.

[3]For more details see Appendix

[4]This is mainly due to the fact that, because it uses a penalty that is part ℓ_1 and part ℓ_2, this procedure works almost as well as the LASSO when the LASSO does best; but it also improves on the LASSO when the LASSO is dominated by the Ridge regression. This is usually the case if there exists high correlations among predictors, as in our case when we consider a large set of macroeconomic indicators (Tibshirani (1996)). As a consequence, the elastic-net penalty outperforms LASSO while preserving the sparse property (Zou and Hastie (2005); Mol et al. (2009a)).

3.1.2 Machine Learning Experts

For each country we also include one Random-forest expert (**Rf**) with country-specific variables and one Random-forest expert (**Rfp**) with all the panel variables. We also include a General Additive Model (**GAM**) whose country specific variables are selected according to the same AUROC criteria as above (see Appendix for details on all the machine learning experts). We have a total of eleven experts for each country. Our models incorporate various horizons of changes for the variables so that inflexion points can be captured. Some models are estimated on a panel, others are estimated country by country but include a foreign sector. Therefore our experts incorporate information from the *entire set of countries* and account for potential interactions and global effects.

4 A Tale of two Centuries

Predicting financial crises from the 1920s out-of-sample in seven countries as diverse as France, Germany, Japan, Netherlands, Spain and the United States on a long period of time may seem like a hopeless enterprise, an economist's folly. Models are estimated using a limited set of variables on a short period a long time ago (between 1896 and 1922). Each country has very different institutions and macroeconomic policies and crises have struck at very different points in time. Japan for example had crises in 1871, 1890, 1907, 1920, 1927 and 1997 while the US had crises in 1873, 1893, 1907, 1929, 1984 and 2007. A striking feature of timing of crises is that many of them occurred at the end of the 19th century and until the 1930s or after 1990 but none during the post world war II period until the 1980s. Eichengreen and Portes (1987) have noted the similarities between the 1930s and the 1980s in their work on the anatomy of financial crises. It will be important therefore to be able to predict the post war tranquil period as well as the sudden resurgence of financial instability in the US and in Japan and in Europe in the 80s and the 90s.

There is a first "global wave" of systemic crises in the 1930s as most of the countries in our sample had a financial crisis around then (US 1929, Spain 1931, Portugal 1931, Japan 1927, Italy 1930, France 1930; only the Netherlands experience a crisis much later in 1939). According to Eichengreen and Portes (1987) the 1920s were marked by two changes which increased the international financial system's susceptibility to destabilizing shocks: the end of the classical gold standard and the associated turmoils in the foreign exchange market with a "gold shortage" and the misalignment of currencies in the 1920s -the pound sterling in particular was largely overvalued; a rapid institutional change in the banking system as the US replaced the UK as the main external creditor with dramatic shifts in the volume and

direction of international lending and rapidly mounting indebtedness in the periphery, in particular Central Europe and Latin America. US investments to the Far East were also important. Much of the business going through relatively inexperienced American hands may have increased the market's tendency to excessive risk taking. Each of these developments had its immediate origins in the dislocations associated with World War I. Massive capital flows out of periphery economies took place as the US stock market boomed. After peaking in the summer of 1928, capital flows fell by 46 per cent within a year. Then commodity exports declined abruptly following the U.S. cyclical downturn commencing in the summer of 1929. Even after suspending convertibility of their currencies, many countries found it impossible to service their external debt. The Great Depression prevented governments to generate enough tax revenues to service debt and after 1930, many Latin American and European countries defaulted. But a more serious threat to the stability of banking systems came as bank deposits started to be liquidated by foreign investors in order to repatriate liquidity to their domestic economies. The run on the Austrian Credit Anstalt in May 1931 created more turmoil. The US banking system suffered considerably unlike the UK banking system which turned out to be resilient despite a run on Sterling in 1931. If 1929 is the base at 100, UK bank shares were at 92 in 1930 and 104 in 1933 while US bank shares were at 67 in 1930 and 15 in 1933 (from the League of Nations 1934). The US banks were particularly vulnerable because they were very exposed the security market and to real estate. The Federal Reserve could not prevent widespread bank failures, nor break the doom loop between the financial markets and the real economy, which ultimately led to the Great Depression. Banking regulation, the second world war and Bretton Woods transformed the financial system and redrew the international monetary order. The creation of the IMF, a more regulated banking system and restrictions to international capital mobility created the conditions of a quiet period between 1945 and the 1980s at least as far financial crises are concerned.

After that tranquil post world war II period, crises started to appear again after the collapse of Bretton Woods, just like the collapse of the classical gold standard preceded the Great Depression. Increased capital mobility is likely to have played a major role. Crises resumed in the 1980s and 1990s but, unlike in 1929, their timing was idiosyncratic across countries. The Latin American debt crisis unfolded in the 1980s after the second oil shock and after the US real rate went through the roof, rendering the cost of servicing external debt in dollars really high. The US experienced the savings and loans crisis in 1984 while Japan experienced a systemic financial crisis in 1997 after the bursting of the real estate bubble at the beginning of the 1990s. Spain had a crisis in 1977 but not Portugal while Italy experienced a crisis in 1990 linked to an economic slowdown and a fragile banking system. Thus it will also be important for our algorithm to predict the idiosyncratic timing of the crisis in

the different countries after the first "global wave" of financial crises around 1929 and the quiet Bretton Woods period.

The second "global wave of crises" occurred around 2008 (US 2007, France 2008, Italy 2008, Netherlands 2008, Portugal 2008, Spain 2008; only Japan is spared). It can be traced to the collapse of Lehman Brothers and the high degree of leverage in the banking system in the US and Europe due to lax regulation and cheap liquidity. Real estate bubbles in a number of countries (US and Spain in particular) made the financial system more fragile as well while highly indebted households amplified the economic downturns. That wave of crises, just like the 1930s, seem to have been caused by an unchecked credit boom among euphoric valuations in real estate markets and securities market more generally at a time of financial innovation and deregulation. The parallels between the excesses of the financial system in the 1920s and the 1990s have been documented in particular by Resheff and Philippon (2012).

4.1 Countries experiences

We present the probability of systemic crises predicted out-of-sample from the beginning of the 1920s for our seven countries. We start with the United States as it has been the hegemon of the global financial system during a large part of the 20th and 21st centuries (see Gourinchas and Rey (2007a) and Gourinchas and Rey (2007b)) and it is at the centre of the Great Depression.

United States

Figure 1 shows our estimated probability of systemic financial pre-crisis out-of-sample in the US between 1906 and 2016, i.e. for more than a century. The purple areas are the year of systemic financial crises according to the macro history data set and the blue bars are the pre-crisis periods (three year before the crises). We are attempting to predict the blue bars: a perfect outcome would be to predict a probability close to 1 for the blue bars and close to 0 everywhere else (including during the actual crisis –purple bars). The results are very good: the probability is very high from the beginning of the sample until 1907 (crisis 1907), goes down and spikes very steeply again in 1926 to 1929 (there is however a smaller spike as well in 1913-14). There is afterwards an alert between 1932 and 1935 at a time of financial distress in the United States and smaller ones around 1953. But, on the whole the probability of a pre-crisis is very low from the early 1950s till 1981 where its spikes again between 1981 and 1984 just before the Savings and Loans crisis. After coming down very significantly it spikes between 2004 and 2007. We show the RMSE and the AUROCs on the

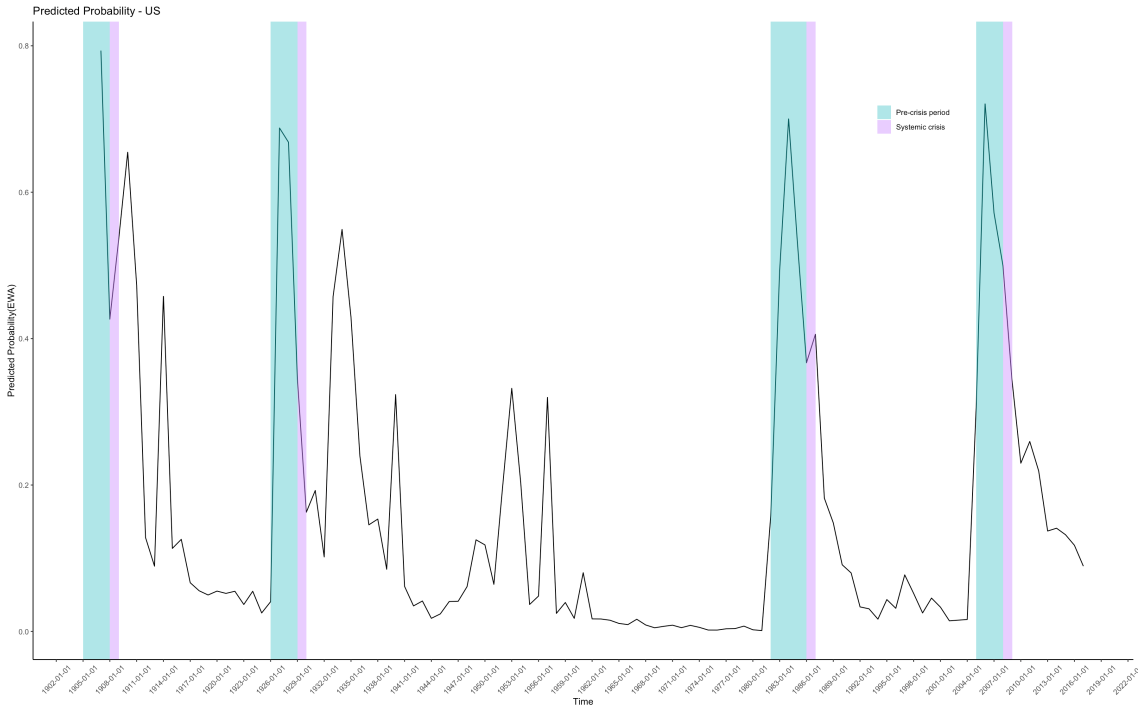


Figure 1: United States

Aggregation Rules	RMSE	AUROC
EWA	0.24	0.94
Best convex	0.20	0.97

Table 2: US

entire forecasting periods in Table 2. The aggregation strategy works well as our estimate is close to the best convex combination of experts (known ex post). In theory the two converge asymptotically. The AUROC is close to 1 at 0.94 indicating that this methodology performs very well in terms of identifying crises and not having many false positives.

Figure 2 presents the weights carried by each model in the forecast. The higher the weights the more informative the model is to predict crisis. There is no causal implications but knowing which set of variables carries more weight may be informative to understand where imbalances in the financial sector lie and do further investigations. In the case of the US, **lc4**[5], **lc1**[6], **Rf, Rfp** seem the most important models. In Figure 3, where the pre-crisis periods are shown in dashed lines, we show which models give the signal of the crisis three years ahead. For the 1929 crisis the dominant two models are **lc4** and **lc1** just like in the 2008 crisis, underlining the combined importance of stock markets, credit (loans and mortgages),

[5]**USlc4**'s variables are Stock prices, Loans, Mortgages, Debt-to-GDP.
[6]**USlc1**'s variables are Long-term interest rate, Real GDP per capita (index), GDP, Broad money.

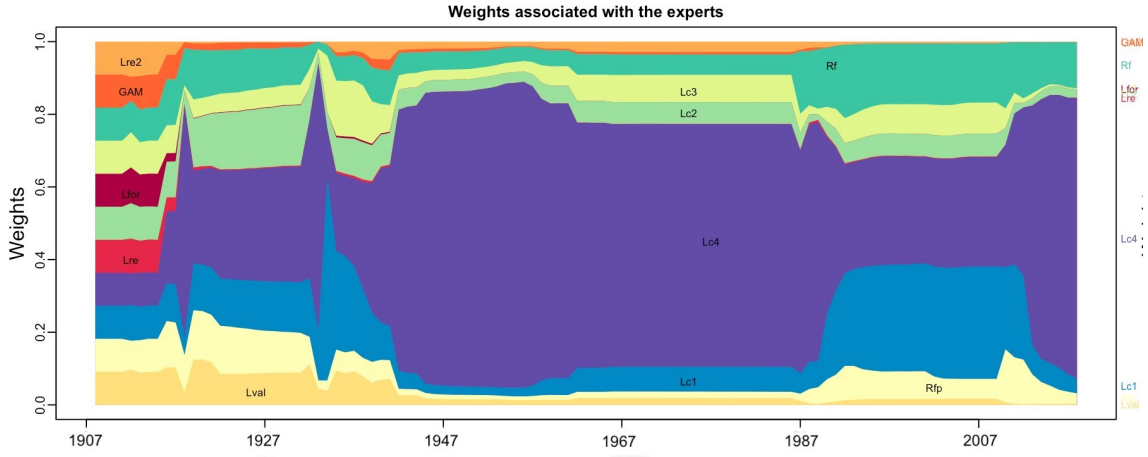


Figure 2: United States

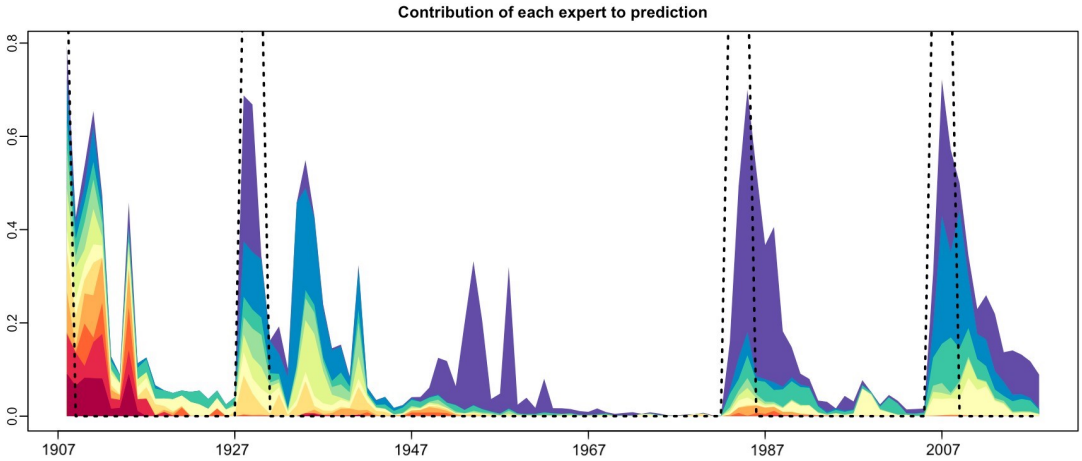


Figure 3: United States

long term interest rate, debt to GDP, economic activity (GDP and real GDP per capita) and monetary conditions (broad money). In both cases the random forests (especially estimated on the whole panel) are also very informative. For the 1930s (false alarms) the domination of **lc1** shows the preeminent role of economic activity, broad money and long term interest rate. In contrast for the 1950s false alarms and for 1984 it is **lc4** (loans, mortgages, debt to GDP and stock prices) which is very dominant. These subsets of variables fit well with the ex post narrative of the 1929 crisis (stock market boom and leverage, cyclical downturn), of the 1984 crisis (savings and loans debacle) and of the 2008 crisis (exuberant valuations and central role of leverage and of the real estate market like in 1929).

Among European countries France, the Netherlands and Portugal have only one post world war II crisis (2008) according to the macro history data set.

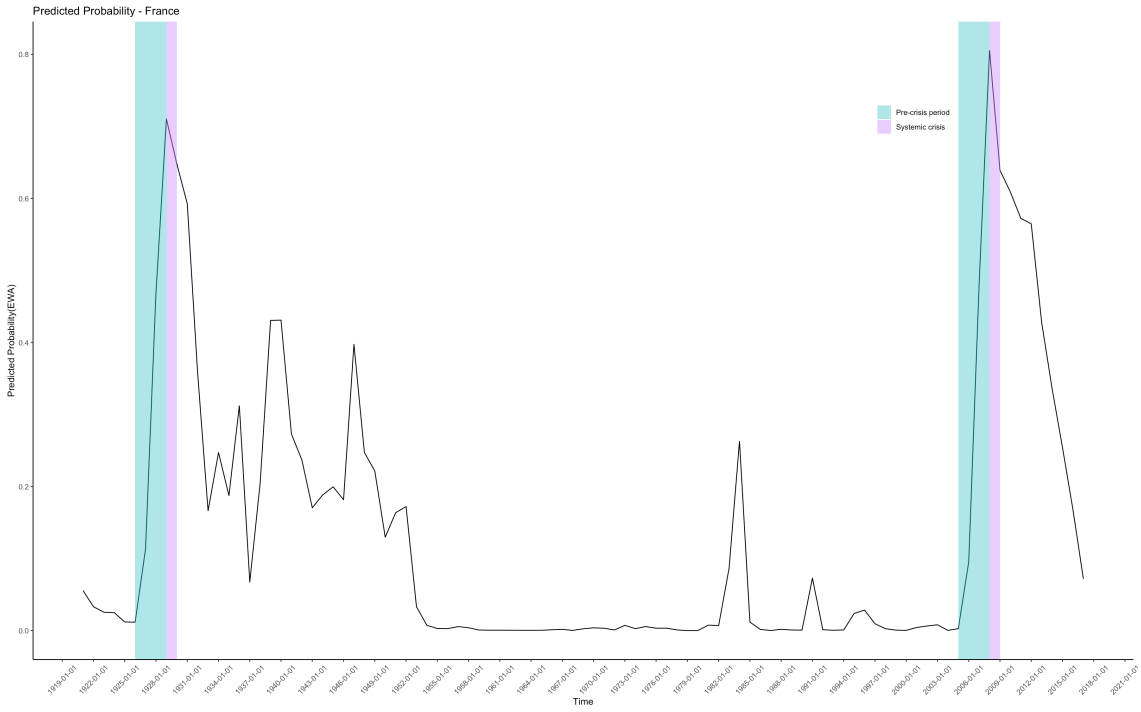


Figure 4: France

France

For France, the crisis linked to the Great Depression, occurred in 1930; the subsequent crisis was in 2008.

Figure 4 shows a very good ability of the on-line learning framework to predict the 1930 and 2008 crisis, with a probability of crisis very close to zero between 1950 and 2008. The probability of crisis does not go down quickly after 2008 (this is unlike the US) and it is still elevated in 2012. This can be linked to the euro area crisis. There is a small spike in 1982 (false alarm) which may have been linked to the second oil shock and the large external deficit following major changes in economic policies and tiny spikes around 1992 at the time of the ERM crisis. We have however a number of false alarms between 1936 and 1946, a very troubled period in French history which spans the second world war. The EWA strategy does as well as the best convex combination of experts and is even better in terms of AUROC. The AUROC and the RMSE are however not as good for France as in the case of the US as shown in Table 3. This probably means that the quality of our set of experts is not as high as it was for the US.

Figure 5 presents the most important models for the forecast and Figure 6 shows their contribution in terms of giving the signal of a crisis three year-ahead. For 1930, **lre2**[7] is the

[7] **lre2**: GDP, Investment-to-GDP ratio, Consumer prices, Exports.

Aggregation Rules	RMSE	AUROC
EWA	0.28	0.85
Best convex	0.28	0.80

Table 3: France

most important but **lre**[8], **lfor**[9], **GAM**[10] and **lc4**[11] also seem to play a role. The most important warning in 1930 comes therefore from real economic activity, investment inflation and the external sector as experts containing external variables are systematically picked (exports, imports, exchange rate, current account). The stock market, government expenditure and house prices are also present to a lesser degree. For 2008, **lc2**[12] is the most important model but **lre2**[13], **rfp**,**lval**[14], **Rf**, **lc1**[15] also contribute. This makes the 2008 crisis relatively similar to the 1930 crisis in France though a little less linked to external sector variables and more linked to valuation variables (short and long interest rates, stock prices, house prices).

The euro area crisis is mostly predicted by the same models in particular **lc2** but **lc4**[16] and **GAM**[17] now also play a role.

The false positives linked to the second world war can be related to **GAM**, **Lfor** and **Lre**. They therefore seem mostly due to real economic activity and the external sector. The small spike in 1982 is related to valuations **Lval** and to **Rf**.

The Netherlands

The Netherlands experienced crises in 1921, 1939 and 2008. Our methodology gives an increase of crisis probability before 1921 but the spike is relatively small and there are some false positive around 1929. But it picks up really well the 1939 crisis as well as the 2008 crisis.

The diagnostics (AUROC and RMSE) are very good as shown in Table 4. In that case, unlike France, we seem to have very good experts but more difficulty approximate the best convex combination of experts ex ante as the RMSE of the EWA is at 0.26 significantly above its theoretical asymptotic value of 0.21.

Figure 8 shows the weights of the different models while Figure 9 indicates which models

[8] **lre**: Real GDP per capita, Real GDP per capita (index), GDP, Consumer prices.
[9] **lfor**: Current account, Imports, Exports.
[10] **FranceGAM**: Real GDP per capita, GDP, Exchange Rate.
[11] **FranceLc4**: Stock price, Government expenditure, House price, Exchange rate.
[12] **FranceLc2**: Long-term interest rate, Real GDP per capita, House price.
[13] **lre2**: GDP, Investment-to-GDP ratio, Consumer prices, Exports.
[14] **Lval**: Short-term interest rate, Long-term interest rate, Stock prices, House prices.
[15] **FranceLc1**: Real GDP per capita, GDP, Exchange rate, Exports.
[16] **FranceLc4**: Stock price, Government expenditure, House price, Exchange rate.
[17] **FranceGAM**: Real GDP per capita, GDP, Exchange Rate.

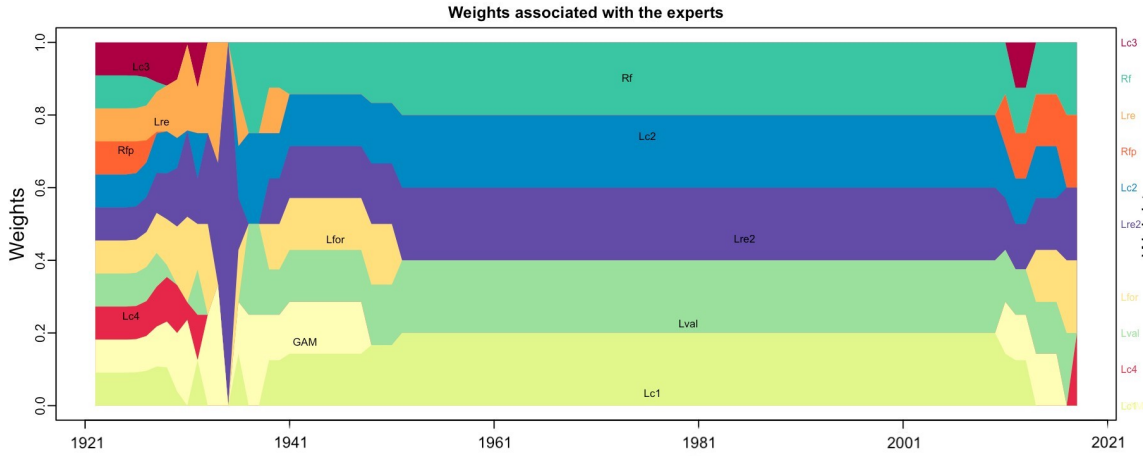


Figure 5: France

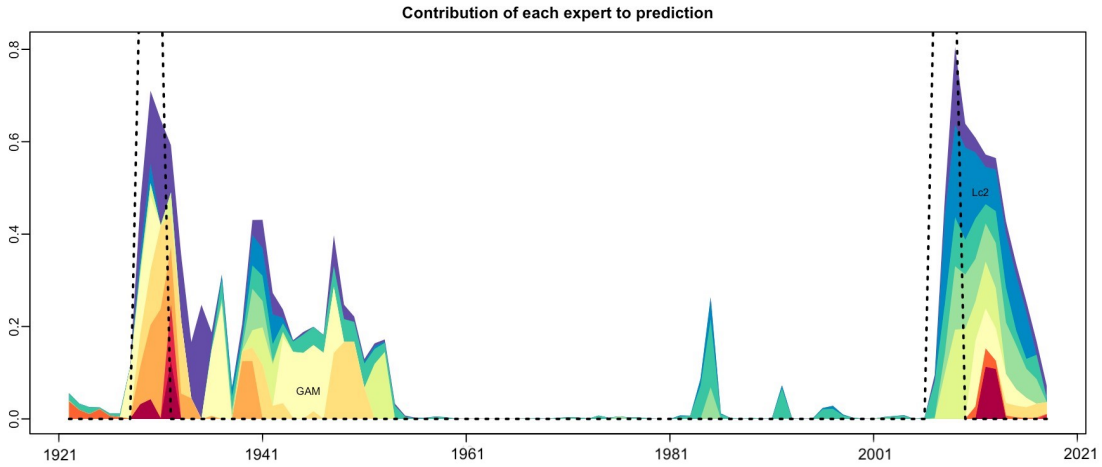


Figure 6: France

Aggregation Rules	RMSE	AUROC
EWA	0.26	0.86
Best convex	0.21	0.96

Table 4: Netherlands

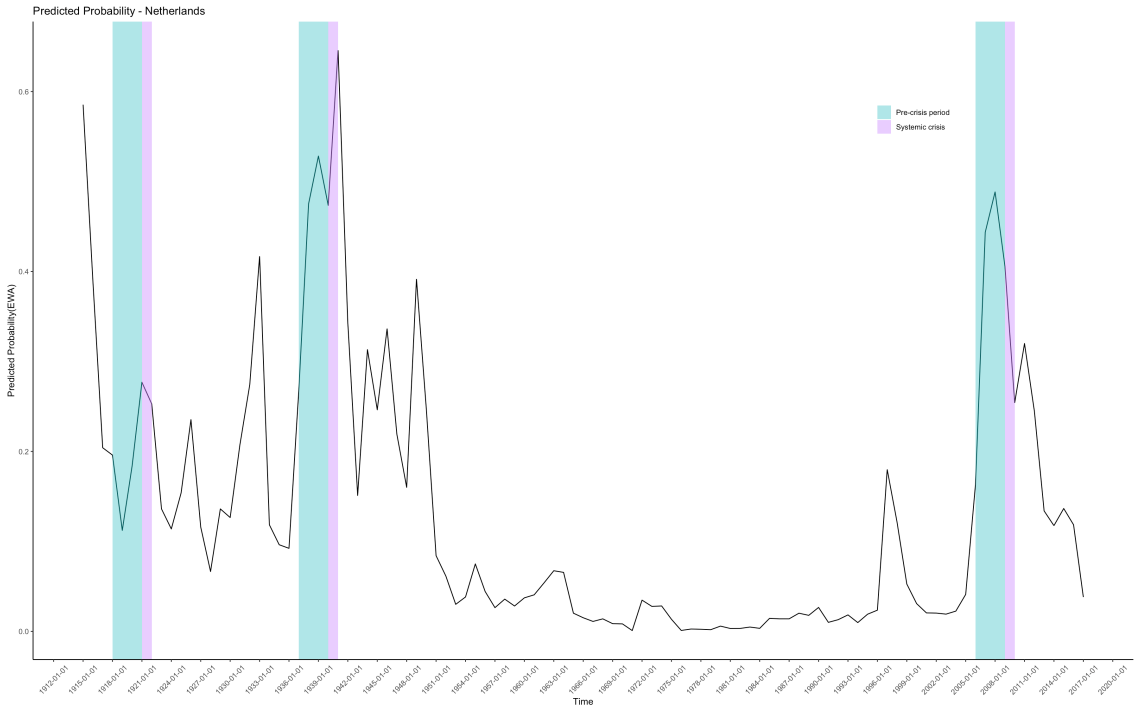


Figure 7: Netherlands

have given the signal.

For 1921, the model **Lval**[18] is the one flashing red. The crisis at the time was in part due to the collapse of the German economy, a close trading partner. The false positives around 1929 are due to **Lval** but also **Lc2**[19] and **Rf**. The false positives in the 1940s are due to **Lval** and **Lm**[20] In contrast one model is clearly dominant to predict 1939 and this is **Lc3**[21]. These variables reflect the economic shock of the Great Depression which affected the Netherlands a bit later than most countries. **Lc3** is still influential to predict 2008 but it is combined with **Rp**, **Lval** and **Lc2**. These variables reflect in particular the influence of the housing market and valuations in the 2008 crisis. In that, it is relatively similar to the US.

Portugal

Portugal has crises in 1920, 1923, 1931 and 2008. 5 shows a very good performance of our forecasting strategy both in terms of aggregation and in terms of performance of the experts with very low RMSEs and AUROCs close to 1.

[18] **Lval**: Short-term interest rate, Long-term interest rate, Stock prices, House prices.
[19] **NetherlandsLc2**: Long-term interest rate, Real GDP per capita, House price.
[20] **Lm**: Narrow Money, Broad Money, Short-term interest rate, Long-term interest rate.
[21] **NetherlandsLc3**: Investment-to-GDP ratio, Consumer price, House price.

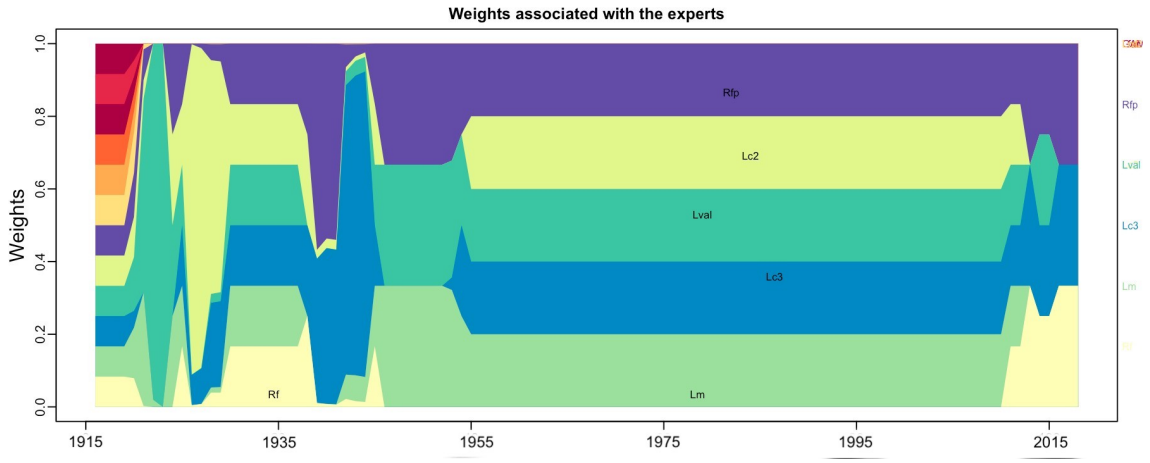


Figure 8: Netherlands

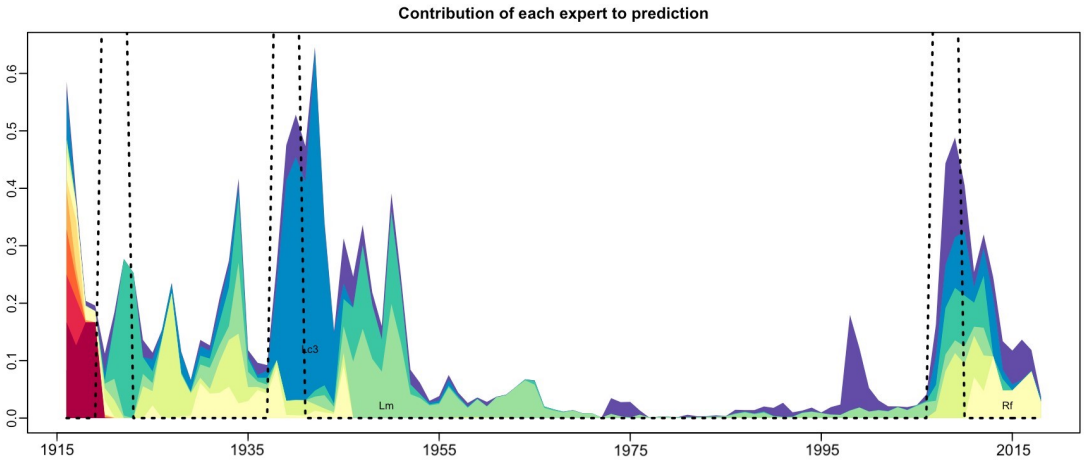


Figure 9: Netherlands

Aggregation Rules	RMSE	AUROC
EWA	0.24	0.89
Best convex	0.21	0.95

Table 5: Portugal

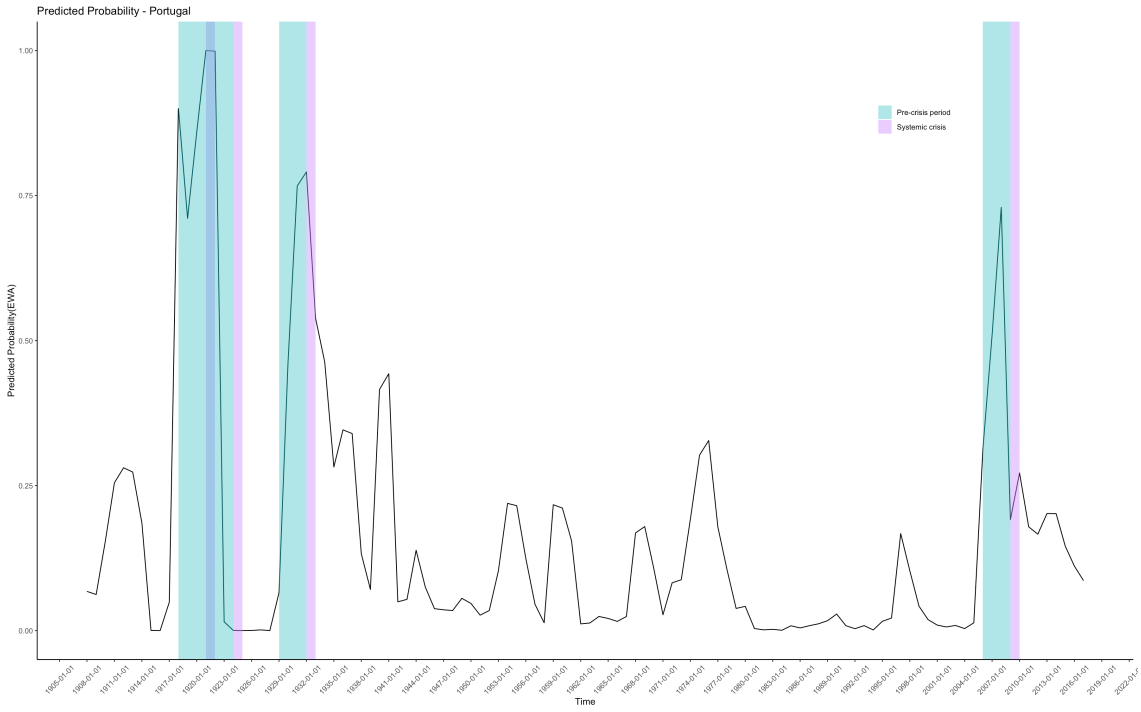


Figure 10: Portugal

1920 and 1923 are predicted by **lre2**[22] and by **lfor**[23]. 1931 is predicted by the same models and by **lre**[24]. The same models and **Rfp** predict 2008. They also give a (false) signal together with **lc4**[25] during the euro area crisis. So the set of models predicting crises in Portugal tend to be stable over time, they involve real activity (GDP, investment, prices) and the external sector (exports, imports, current account).

Spain

Spain's crisis pattern is different from France, Netherlands and Portugal as it had two crises after the second world war: beside 2008, it also experienced a crisis in 1977. So, in our forecasting sample, Spain had crises in 1924, 1931, 1977 and 2008. The AUROCs and RMSE are shown in Table 6. As in the other cases, tehy show a high signal to noise ratio.

The 1931 crisis is linked to the Great Depression. According to our algorithm, it is mostly predicted by the expert **Lm**[26]. The false positives in teh 1930s are linked to **Lm** but also to **Lre** and **Lre2**, which is reminiscent of what we found for Portugal. The 1977 crisis was caused

[22] **lre2**: GDP, Investment-to-GDP ratio, Consumer prices, Exports.
[23] **lfor**: Current account, Imports, Exports.
[24] **lre**: Real GDP per capita, Real GDP per capita (index), GDP, Consumer prices.
[25] **Portugallc4**: Narrow money, gdp, short-term interest rate.
[26] **Lm**: Narrow Money, Broad Money, Short-term interest rate, Long-term interest rate.

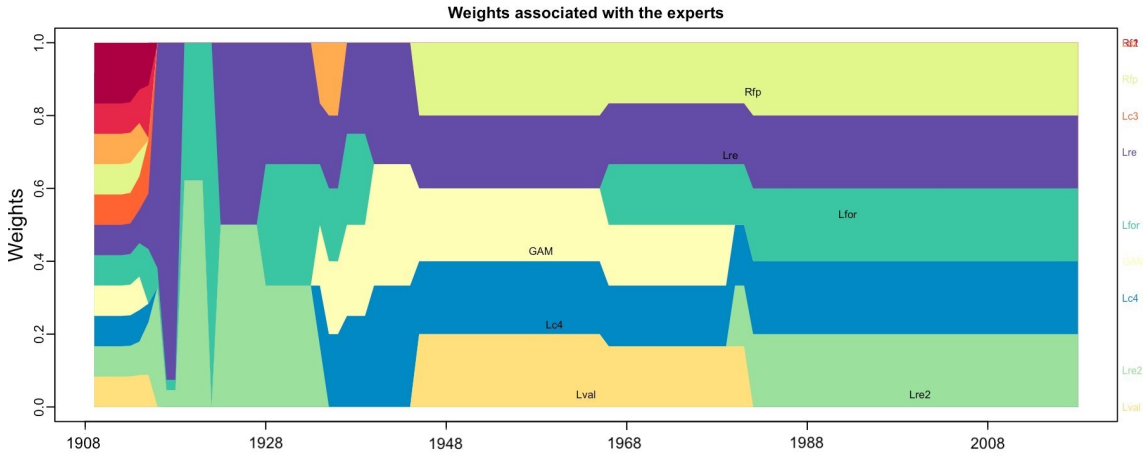


Figure 11: Portugal

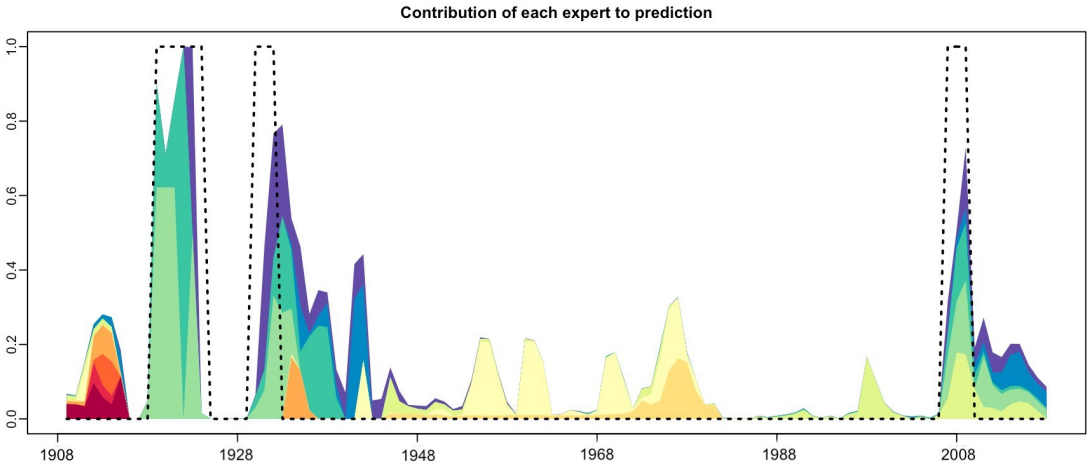


Figure 12: Portugal

Aggregation Rules	RMSE	AUROC
EWA	0.30	0.85
Best convex	0.26	0.92

Table 6: Spain

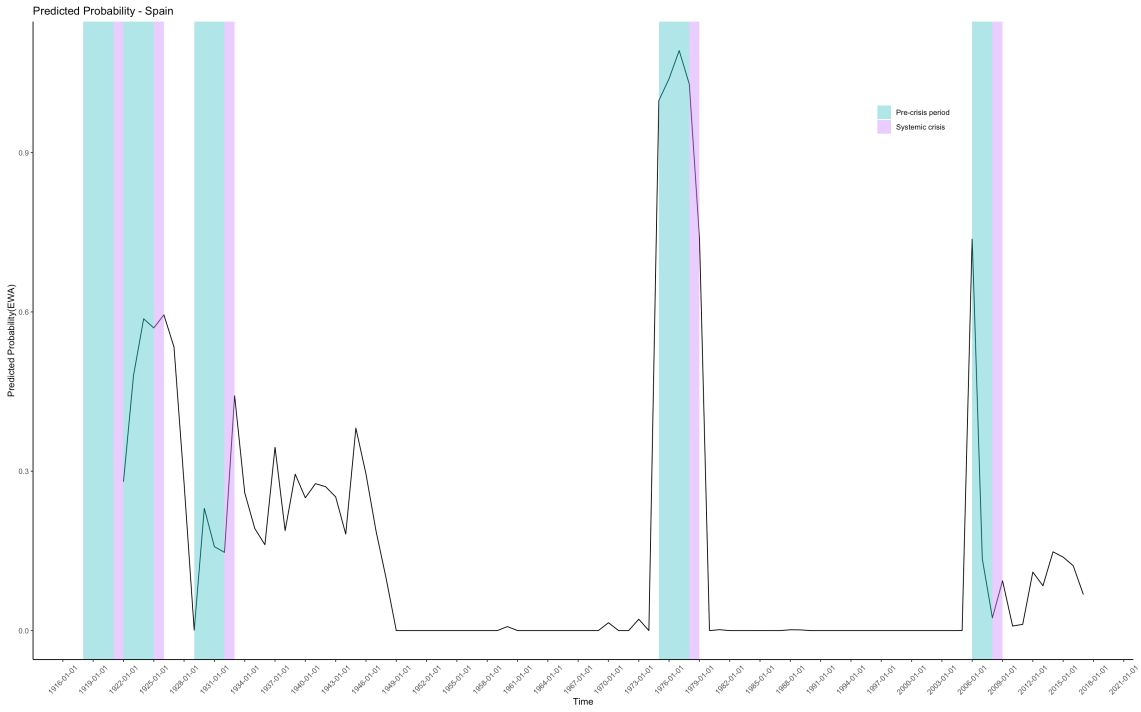


Figure 13: Spain

Aggregation Rules	RMSE	AUROC
EWA	0.38	0.70
Best convex	0.29	0.87

Table 7: Italy

by a deterioration of the current account due to the first oil shocks, a drop in investment and an exchange rate crisis with a big devaluation of the peseta. Interestingly, the expert picked by our algorithm ex ante is **Lc2**[27] which fits perfectly the ex post narrative of the crisis. The 2008 crisis is picked up by the **RFp** model.

Italy

Italy, like Spain had 4 crises in our forecasting sample out of which two are post world war 2. Italy had systemic crises in 1930, 1935, 1990 and 2008.

Just like for Spain we are able to forecast the first post war crisis even though it occurs at a very different times from Spain (1990 versus 1977). The diagnoses are good though our early warning signals do not seem to be quite as precise as in the case of Spain (see 7). Though we get some false positives during the euro area crisis time (which is not counted

[27] **Lc2**: Investment-to-gdp ratio, Exports, Exchange rate.

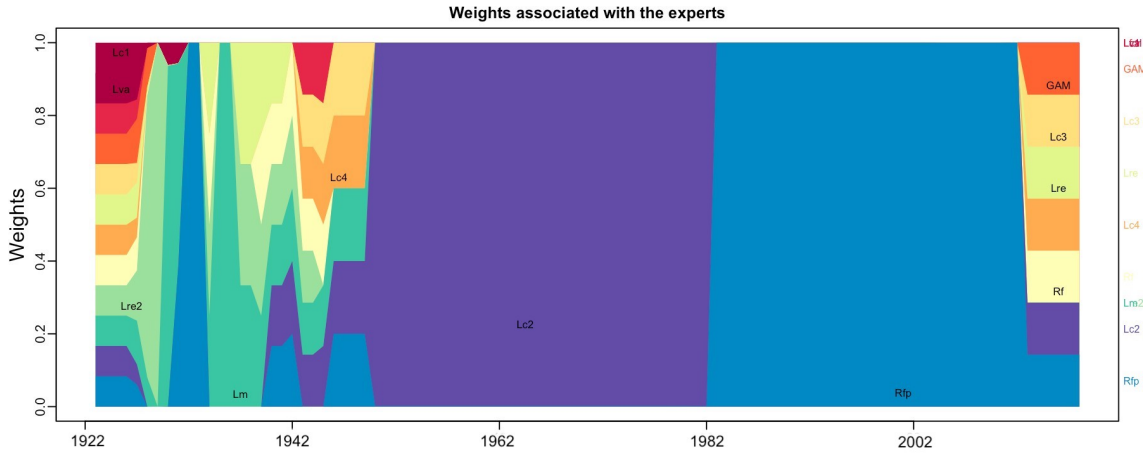


Figure 14: Spain

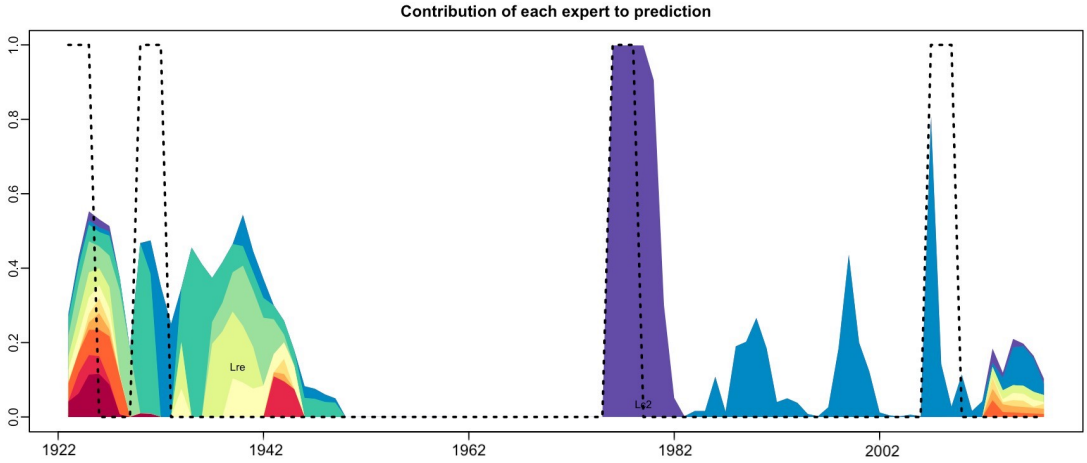


Figure 15: Spain

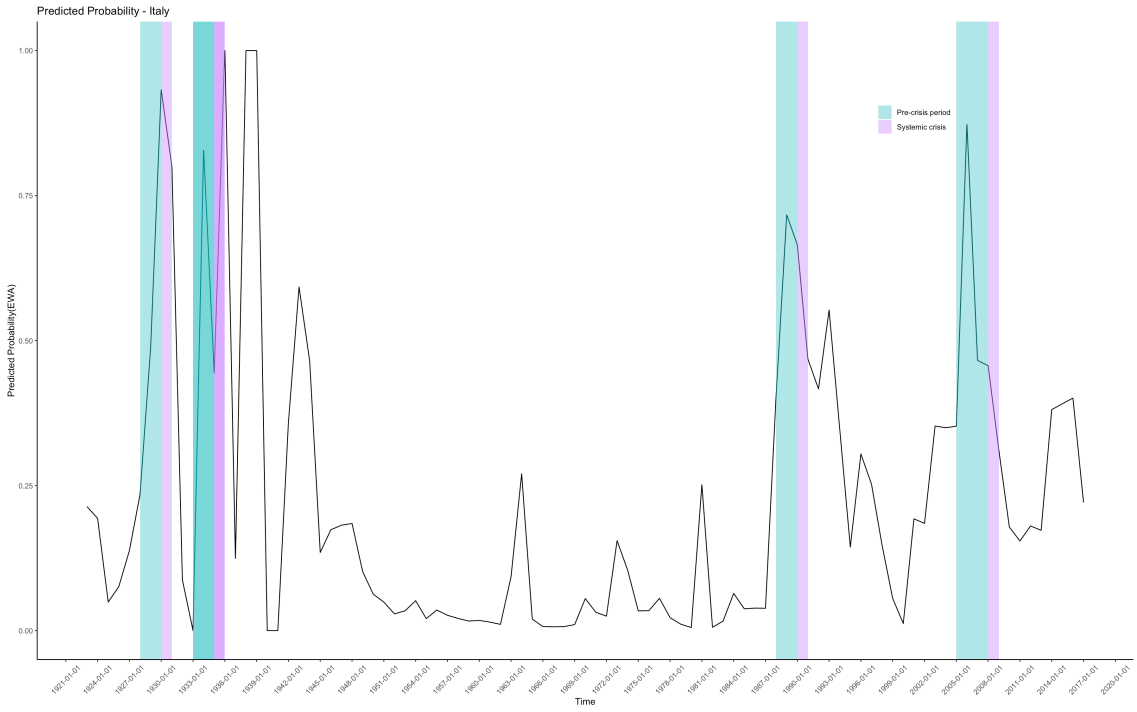


Figure 16: Italy

as a systemic crisis) in the macro history data set and in the 1930s.

The model which predict 1930 (crisis linked to the Great Depression) is mostly **Lc3**[28] and the model which predicts 1935 is mostly the **GAM**[29]. For the 1990 crisis, the models which contains the most information are again **Lc3** and **GAM** but also **Lc2**[30] and **Rf**. The 1990 crisis is Italy was due to the distress of many small banks especially in the South in a context of slow economic growth. For the 2008 crisis it is **GAM**, **Lc3** mostly but also **Rf** and **Lc2** who give the signals and keep the probability of a crisis relatively elevated during the euro area crisis.

Japan

The final country we study is Japan, which is a very interesting case as it is well known that the burst of the land price bubble in Japan around 1990 led to to a very prolonged period of low growth and has been seen by many as very comparable to 2008. But Japan was very idiosyncratic in the timing of its crises. On our forecasting sample, the Japanese crises are in 1920, 1927 and 1997. Our methodology works well nevertheless as documented in Table 8.

[28] **ItalyLc3**: Long-term interest rate, Real GDP per capita, USD Exchange rate.
[29] **ItalyGAM**: Real gdp per capita (3y), Population(3y), Loans (1y).
[30] **ItalyLc2**: Consumer price, Loans, Exports.

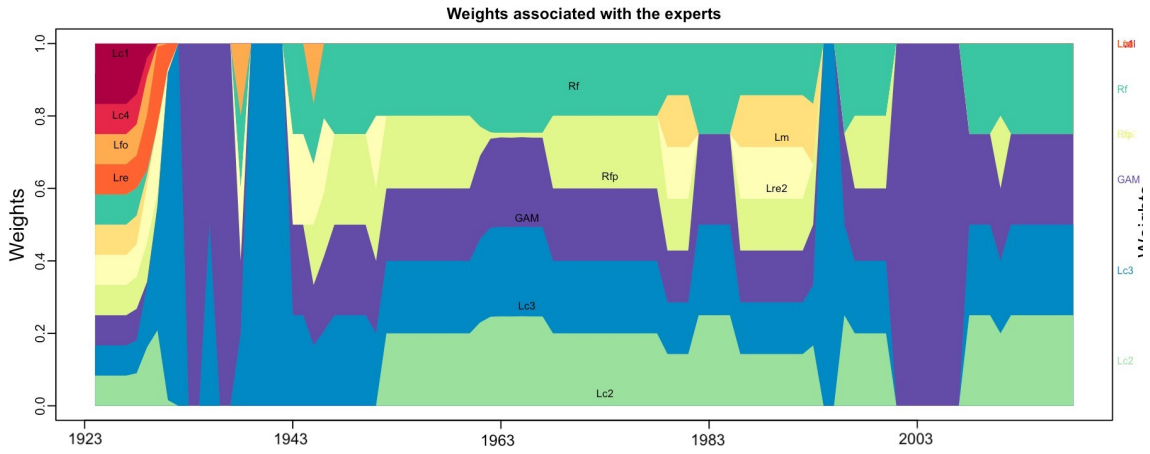


Figure 17: Italy

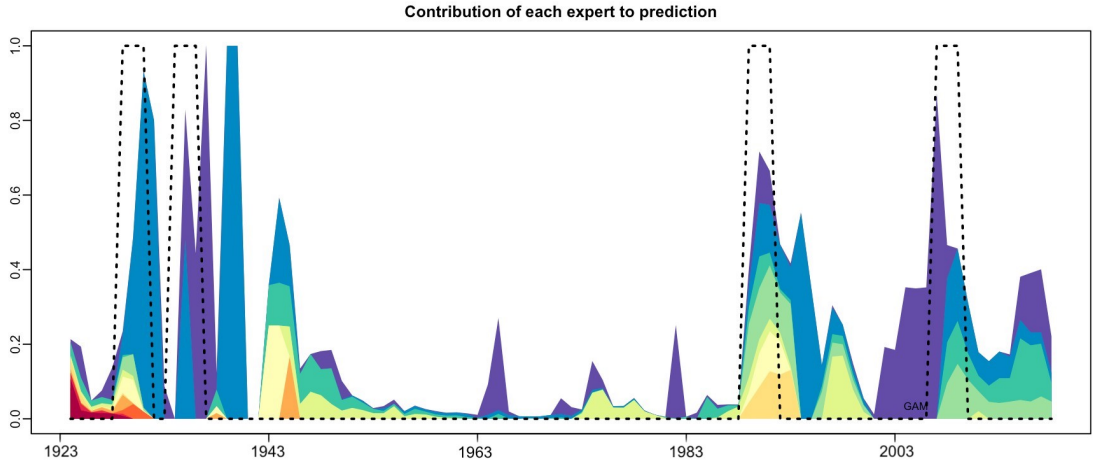


Figure 18: Italy

Aggregation Rules	RMSE	AUROC
EWA	0.27	0.82
Best convex	0.24	0.92

Table 8: Japan

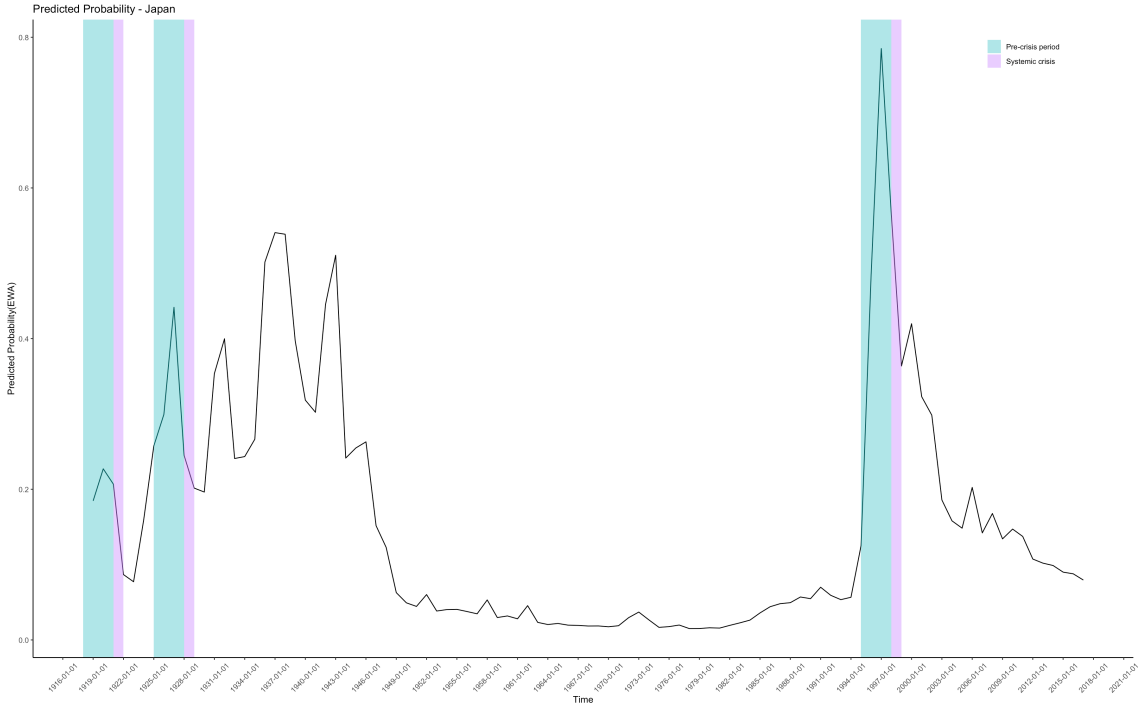


Figure 19: Japan

The models predicting the 1920 and 1927 crises are numerous but the most important ones are **Lm**[31] **Rf** and Lc3[32]. For 1997 however it is Lc4[33] and **Lval**[34] mostly, with **Rfp** also playing a role. This is again consistent with a crisis due to a bubble bursting and affeting the financnail sector an dhe real economy. It is also inetresting that the variable population is picked up both in Japan and in Italy which are two countries were the aging of the population is considered to have been an issue.

[31] **Lm**: Narrow Money, Broad Money, Short-term interest rate, Long-term interest rate.
[32] **JapanLc3**: Long-term interest rate, Real GDP per capita, USD Exchange rate
[33] **JapanLc4**: Loans, population, Real GDP per capita.
[34] **Lval**: Short-term interest rate, Long-term interest rate, Stock prices, House prices.

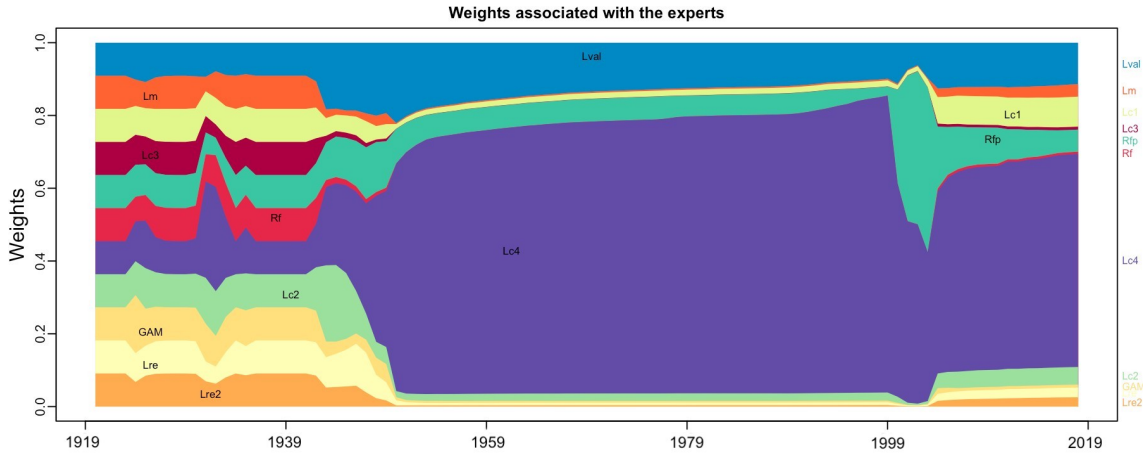


Figure 20: Japan

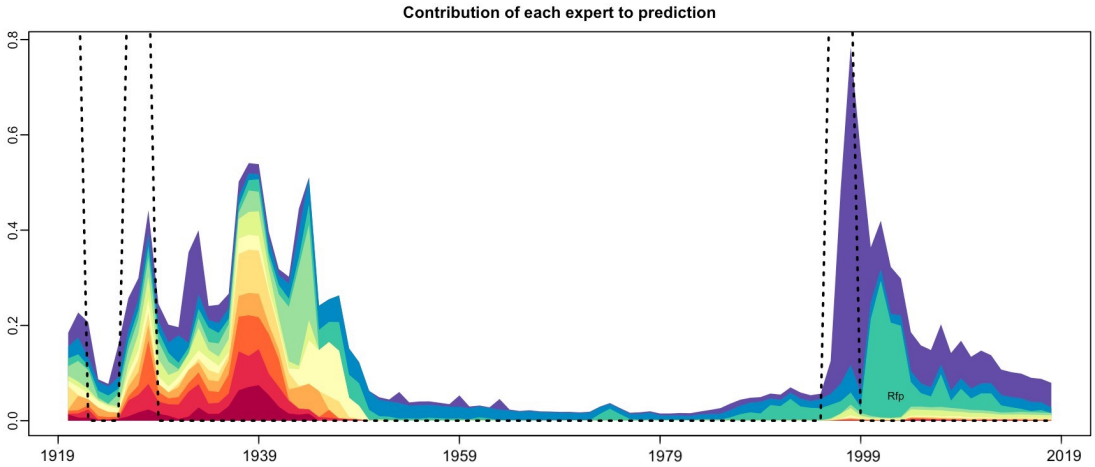


Figure 21: Japan

5 Conclusions

We find that, surprisingly, a simple machine learning algorithm optimal model aggregation using a limited set of models estimated on the period 1896-1922 is able to predict all subsequent systemic crises in countries as diverse as the US, Japan and European countries including France and Italy. Hence Reinhart and Rogoff are right: there is enough information in the 1896-1922 crises to predict the Great Depression and 2008 out-of-sample in all countries. But we can also predict idiosyncratic country crises (Japan 1997, Italy 1990 etc...) with the same information What is also true is that the variables that are key to give an early warning are not necessarily the same in the 1930s and in the 1990s-2000s. But we have enough information to pin them down. The variables selected ex ante by our algorithm tend to fit the ex post narrative of the crises quite well. There are some false positive but often they correspond to turbulent times: the 1940s or the euro area crisis (which is not counted as a systemic crisis). Interestingly we have no false positive during the entire period post war up to the 1980s, which indeed was a very tranquil period as far as financial crises are confirmed.

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Appendix

6 Sequential learning

Algorithm 1. ***Prediction with expert advice and delayed feedback***

1. *The expert advice* $\left\{f_{j,t} \in \mathcal{D} : j \in \mathcal{E}\right\}$ *is revealed to the forecaster.*
2. *The forecaster makes the prediction* $\hat{y}_t \in \mathcal{D}$.
3. *The t-3 observation* y_t *is revealed.*
4. *The forecaster and each expert respectively incur losses* $\ell(\hat{y_{t-3}}, y_{t-3})$ *and* $\ell(f_{j,t-3}, y_{t-3})$.

Algorithm 2. ***Gradient-based EWA***

1. *Parameter : Choose the learning rate* $\eta_t > 0$.
2. *Initialization :* p_1 *is the first uniform weight,* $p_{j,1} = \frac{1}{N} \forall j \in \{1, ..N\}$.
3. *For time instances* $t = 2, 3, ..., T$ *the weights vector* p_t *is defined by :*

$$p_{j,t} = \frac{\exp(-\eta_t \sum_{s=1}^{t-1} \tilde{L_{j,s}})}{\sum_{k=1}^{N} \exp(-\eta_t \sum_{s=1}^{t-1} \tilde{L_{k,s}})}$$

where $\tilde{L_{j,s}} = \nabla \ell(\sum_{k=1}^{N} p_{k,s} f_{k,s}, y_s) \cdot f_{j,s}$

The strategy $\mathcal{E}_\eta^{\text{grad}}$ competes with the best convex combination of experts. The following theorem is stated in Stoltz (2010):

Theorem 1. *If* $\mathcal{D} = [0, 1]$ *is convex,* $\mathcal{L}(\cdot, y)$ *are differentiable on* $\mathcal{D}$ and $\tilde{\mathcal{L}_{j,t}}$ *are in* $[0, 1]$*, for all* $\eta_t > 0$:

$$\sup\{R_T(\mathcal{E}_\eta^{\text{grad}})\} \leq \frac{\ln(N)}{\eta_t} + \eta_t \frac{T}{2} \tag{1}$$

The bound of the regret depends on three parameters, two exogeneous (N and T) and one endogenous (η_t). An interesting property of the theorem is that the bound does not depend linearly on the number of experts, but on $\ln(N)$. A large number of experts will not drastically increase the difference between the forecaster's cumulative loss and the cumulative loss of the best combination of experts. The last parameter of the bound η_t is the learning rate. For the gradient-based EWA aggregation rule, the forecaster chooses the parameter η_t with the best past performance :

$$\eta_t \in \arg\min_{\eta > 0} \hat{L}_{t-1}(\mathcal{E}_\eta)$$

7 Experts

Elastic-net Logits

The logits with elastic net penalty are constructed following Friedman et al. (2010) as:

$$\min_{\beta_0,\beta}\left\{\frac{1}{N}\sum_{i=1}^{N}F(\beta_0+x_i\beta)-\lambda P_\alpha(\beta)\right\} \text{ and } P_\alpha(\beta)=\sum_{j=1}^{p}[\tfrac{1}{2}(1-\alpha)\beta_j^2+\alpha\,|\,\beta_j\,|\,]$$

Since there is a risk of correlation, we pick $\alpha = 0.7$. All the Logits include each variable in level as well as the 1-year change, the 2-year change and the 3-year change.

Machine Learning Experts

Random Forest
A random forest (**RF**) consists in three steps :

- Build a number of decisions trees on bootstrapped training samples.
- Each time a split in a tree is considered, a random sample of m predictors is chosen as split candidate.
- Aggregate the prediction of each tree.

General Additive Model
Generalized additive models (**GAM**) provide a general framework for extending a standard linear model by allowing non-linear functions of each of the variables, while maintaining additivity. We consider here a General Additive Model such as :

$$y_t = \beta_0 + f_1(x_{1,t}) + f_2(x_{2,t}) + f_2(x_{12t})$$

The model is fitted with smoothing splines [see Hastie and Tibshirani (1986)].

Common experts across countries

We have 4 logits and two machine learning experts which are common to all countries.

- Logit real economy (lre) : Real GDP per capita, Real GDP per capita (index), GDP, Consumer prices.
- Logit real economy 2 (lre2) : Gdp, Investment-to-GDP ratio, Consumer prices, Exports.
- Logit valuation (lval) : Short-term interest rate, Long-term interet rate, Stock prices, House prices.
- Logit foreign (lfor) : Current account, Imports, Exports.
- Random-forest (Rf) : country-specific.

- Random-forest (Rfp) : panel.

We then have four logits and a machine learning expert (GAM) which are country specific. Their variables have been selected as having the highest AUROCs on the batch sample (see the section on Variables selection for logit combinations below).

Country-specific experts

United States

- Logit combination 1 (Lc1) : Long-term interest rate, Real GDP per capita (index), GDP, Broad money.
- Logit combination 2 (Lc2) : Long-term interest rate, Debt-to-GDP ratio, Exports.
- Logit combination 3 (Lc3) : Long-term interest rate, Narrow money, Real GDP per capita,
- Logit combination 4 (Lc4) : Stock prices, Loans, Mortgages, Debt-to-GDP
- General Additive Model (GAM) : Imports, Long-term interest rate (2y), Debt-to-GDP ratio (2y).

France

- Logit combination 1 (Lc1) : Real GDP per capita , Gdp, Exchange rate, Exports.
- Logit combination 2 (Lc2) : Long-term interest rate, Real GDP per capita, House price.
- Logit combination 3 (Lc3) : Investment-to-GDP ratio, Consumer price, House price.
- Logit combination 4 (Lc4) : Stock price, Government expenditure, House price, Exchange rate.
- General Additive Model (GAM) : Real gdp per capita, GDP,Exchange Rate.

Italy

- Logit combination 1 (Lc1) : Real consumption, Exports, Narrow money.
- Logit combination 2 (Lc2) : Consumer price, Loans, Exports.
- Logit combination 3 (Lc3) : Long-term interest rate, Real GDP per capita, USD Exchange rate.
- Logit combination 4 (Lc4) : Loans, population, Real GDP per capita.
- General Additive Model (GAM) : Real gdp per capita (3y), Population(3y), Loans (1y).

Japan

- Logit combination 1 (Lc1) : Broad money, Exchange rate, House price, Stock price.
- Logit combination 2 (Lc2) : Loans, House price, Exchange rate.
- Logit combination 3 (Lc3) : Narrow money, House price, Exchange rate.
- Logit combination 4 (Lc4) : House price, Exchange rate, Government expenditure.
- General Additive Model (GAM) : Broad money (1y), Loans (1y), Government revenue (2).

Spain

- Logit combination 1 (Lc1) : Investment-to-gdp ratio, GDP, Exchange rate.
- Logit combination 2 (Lc2) : Investment-to-gdp ratio, Exports, Exchange rate.
- Logit combination 3 (Lc3) : Real GDP per capita, Imports, Exchange Rate.
- Logit combination 4 (Lc4) : Real GDP per capita (index), Imports, Exchange Rate.
- General Additive Model (GAM) : Exchange Rate, Population, Imports (2y).

Netherlands

- Logit combination 1 (Lc1) : Government revenue, Long-term interest rate, House price.
- Logit combination 2 (Lc2) : Expenditure, Short-term interest rate, House price.
- Logit combination 3 (Lc3) : Long-term interest rate,Expenditure, House price.
- Logit combination 4 (Lc4) : Real GDP per capita (index), Expenditure, House price.
- General Additive Model (GAM) : Real GDP per capita (3y), House price (3Y), Government expenditure (3y)

Portugal

- Logit combination 1 (Lc1) : Narrow money, Government revenue, long-term interest rate.
- Logit combination 2 (Lc2) : Consumer price, Broad money, Current account.
- Logit combination 3 (Lc3) : Narrow money, Exports, Exchange rate.
- Logit combination 4 (Lc4) : Narrow money, gdp, short-term interest rate.
- General Additive Model (GAM) : Narrow money (3y), Exchange rate, Consumer price.

Variables selection for logit combinations

1. The variables are selected thanks to an AUROC procedure performed on the batch sample, following Schularick and Taylor [2012] and Coudert and Idier [2017].

2. The number of selected variables in the logit combinations also depends on variables' AUROC. Since regularization is a way to decrease the risk of overfitting when the model complexity increases, adding to much variables decreases the forecasting ability [Hastie and Zou, 2005]. As in Coudert and Idier[2017], we restrain the sets of variables included in the "logit combinations" experts. In our case, 3 to 5 variables are included corresponding to 12 to 20 variables since we always include 1y, 2y and 3y transformations. If several variables have a large AUROC, i.e. superior to 0.7 [Pepe, 2003; Schularick and Taylor, 2012] [35], more variables will be included in the logit combinations.

We report here the AUROC for each selected variable for each country.

1.US

Selected variables	Procedure	AUROC
Long-term interest rate	AUROC	0.92
Real GDP per capita	AUROC	0.74
GDP	AUROC	0.75
Broad Money	AUROC	0.71
Debt-to-GDP ratio	AUROC	0.88
Exports	AUROC	0.74
Narrow money	AUROC	0.72

2.France

Selected variables	Procedure	AUROC
Real GDP per capita	AUROC	0.96
GDP	AUROC	0.95
US Exchange Rate	AUROC	0.92
Exports	AUROC	0.75
Long-term interest rate	AUROC	0.82
House price	AUROC	0.87
Investment-to-GDP ratio	AUROC	0.70
Consumer price	AUROC	0.81
Stock price	AUROC	0.70
Government expenditure	AUROC	0.82

3.Italy

Selected variables	Procedure	AUROC
Real consumption	AUROC	0.55
Exports	AUROC	0.63
Narrow money	AUROC	0.6
Consumer price	AUROC	0.62
Loans	AUROC	0.65
Long-term interest rate	AUROC	0.56
Real GDP per capita	AUROC	0.65
USD Exchange Rate	AUROC	0.61
Population	AUROC	0.66

4. Japan

Selected variables	Procedure	AUROC / PCA
Broad Money	AUROC	0.72
Exchange Rate	AUROC	0.61
House price	AUROC	0.54
Stock price	AUROC	0.52
Loans	AUROC	0.58
Narrow money	AUROC	0.72
Government expenditure	AUROC	0.56

5. Spain

Selected variables	Procedure	AUROC / PCA
Investment-to-gdp	AUROC	0.73
GDP	AUROC	0.70
Exchange rate	AUROC	0.92
Exports	AUROC	0.82
Real GDP per capita	AUROC	0.70
Imports	AUROC	0.78

6. Netherlands

Selected variables	Procedure	AUROC / PCA
Government revenue	AUROC	0.61
Long-term interest rate	AUROC	0.66
House price	AUROC	0.68
Expenditure	PCA	0.65
Short-term interest rate	AUROC	0.56
Real GDP per capita	AUROC	0.80

7. Portugal

Selected variables	Procedure	AUROC / PCA
Narrow money	AUROC	1
Government revenue	AUROC	0.91
Long-term interest rate	AUROC	0.87
Consumer price	AUROC	0.96
Broad Money	PCA	0.99
Current account	AUROC	0.87
Exports	AUROC	0.87
GDP	AUROC	0.96
Short-term interest rate	AUROC	0.77