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An economic and financial exploratory

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Abstract. This paper describes the vision of a European Exploratory for economics and finance using an interdisciplinary consortium of economists, natural scientists, computer scientists and engineers, who will combine their expertise to address the enormous challenges of the 21st century. This Academic Public facility is intended for economic modelling, investigating all aspects of risk and stability, improving financial technology, and evaluating proposed regulatory and taxation changes. The European Exploratory for economics and finance will be constituted as a network of infrastructure, observatories, data repositories, services and facilities and will foster the creation of a new cross-disciplinary research community of social scientists, complexity scientists and computing (ICT) scientists to collaborate in investigating major issues in economics and finance. It is also considered a cradle for training and collaboration with the private sector to spur spin-offs and job creations in Europe in the finance and economic sectors. The Exploratory will allow Social Scientists and Regulators as well as Policy Makers and the private sector to conduct realistic investigations with real economic, financial and social data. The Exploratory will (i) continuously monitor and evaluate the status of the economies of countries in their various components, (ii) use, extend and develop a large variety of methods including data mining, process mining, computational and artificial intelligence and every other computer and complex science techniques coupled with economic theory and econometric, and (iii) provide the framework and infrastructure to perform what-if analysis,

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scenario evaluations and computational, laboratory, field and web experiments to inform decision makers and help develop innovative policy, market and regulation designs.

1 Mission

1.1 Vision

At the most basic level, economics deals with the allocation of scarce resources for the production, distribution, and consumption of goods and services. Finance in its simplest form is concerned with the way in which funds are invested. The way in which funds are allocated involves considerations of time, liquidity, and risks and their interrelations. In broad terms, the interface of the economic and financial system involves the influence of beliefs, forecasts, preferences, hedging needs, psychology and the regulatory environment on the behaviour of economic actors and financial practitioners. It increasingly involves the use of automated (i.e., computer-based algorithmic) trading, leading to much stronger and faster interactions as revealed by the recent so-called flash crashes.

These intrinsic or technologically-driven features play major roles in the economic and financial systems and might be responsible of consequences (either positive or negative) that have been widely quoted for a long time but never properly faced. However, the situation is nowadays significantly different. Firstly, the economic crisis has clearly revealed the weaknesses of standard economic and financial models (e.g., the General Equilibrium Economy (GEE) has no production at all, the Dynamic Stochastic General Equilibrium (DSGE) models have but without any theoretical foundation, none of them include a financial market). Secondly, the standard notions of rationality and optimising behaviour has been severely challenged by behavioural economics and finance. Moreover, economic agents are found to be highly heterogeneous in their preferences, which is not well captured by the representative agent framework. Lastly, the ICT revolution has completely changed the way in which we can analyse the economic world, and has provided us with data hitherto unavailable on how people do actually act (at different levels of granularity in time, space and society).

The research challenges of economics and finance are massive and varied. Rather than shrinking over time, the challenges are growing. As recent and unfolding events illustrate, they include issues of sovereign debt, liquidity, risk, stability, contagion, algorithms behaviour, and the impact of regulatory and taxation regimes. Furthermore, the growing role played by companies such as Google and soon Facebook emphasizes that we can no longer focus on single rational individuals and their isolated choices, nor on highly aggregated variables. Thus, financial-economy can be properly studied only by accepting the fact that it is a complex evolving techno-social system whose models should neatly fill (or more properly overcome) the dogma of separated micro and macro behaviour that has existed for so long. There is a great need for research leading to understanding, followed by the implementation of innovative methods, of the interrelationship between structure, dynamics and function, of the strengths and weaknesses of strongly coupled systems and of interdependent networks and of contagion and cascading effects. All of these are now both scientifically and technically feasible and the data that is needed is there to be organised and analysed and this will be a key part of this project. Essential directions need to integrate ecological and social systems approaches, in order to develop novel concepts to manage complexity, within integrative system design. Together with the above, the understanding of the role and nature of incentive schemes both at the individual and the collective level, in particular, will provide a framework for promoting resilience in the face of looming systemic risks, towards sustainability in a climate of self-reinforcing trust.

For this, new approaches to economics and finance are required that more realistically incorporate the institutional environment, regulations and trading behaviour to make economic models better at explaining systemic (non-idiosyncratic) risk as well as systemic investor/trader decisions, taking into consideration their emotions, the constraints they operate under and their cognitive mechanisms and how these influence decision making [1–5] and, most essentially, the impact of these on collective outcomes. Nowadays, new tools are under development so to analyze market and financial professionals' behaviors. As this new approach to economics/finance develops, it is intensifying the use of quantitative tools and techniques, so that mathematical and statistical methodologies are being employed to understand the constraints, the incentives and biases of decision makers (regulators, fund managers, traders, etc.) and their impact on the markets.

In Science and Engineering, the use of observatories (NOAA, ECMWF, Hubble Space Telescope) and experimental facilities (ex. CERN, Wind Tunnels, Flight simulators) are commonplace. However, in the social science, the use of computational techniques and experimental facilities on a large scale in order to carry out research and inform policy has only emerged recently. This is because the social scientist does not control nor is able to repeat the experiment he is monitoring. However, as shown for instance with the Global Viral Forecasting Initiative concerned with epidemics of diseases (globalviral.org), we are now in a position to access the mass of disparate data on the economic activity and decisions of individuals and firms and thus to constantly monitor the evolution of the economy and to detect the early symptoms of the arrival of major changes.

The European Economic and Financial Exploratory (EEFE) is envisioned as a free independent academic organization at the European level with international partners, which

1. continuously monitors and evaluates the state of the economies of countries and their various components, including the real economy, the governmental sector, the credit side, banking and finance, by developing and managing a massive repository of high-quality data in all economic and financial areas;
2. serves as a platform for the development and application of data mining, process mining, computational and artificial intelligence and every other computer and complex science technique coupled with economic theory and econometric methods that can be devoted to ex-ante forecast (in a time-scale specific to the specific economic area under investigation), with the goal of identifying the emergence of economic risks, instabilities and crises;
3. provides the framework and infrastructure to perform what-if analysis, scenario evaluations and computational experiments to inform decision makers and help develop innovative policy, market and regulation designs.

The challenges and goals of the EEFE that we describe below are in synergy with the ICT development envisioned within the FuturICT [6].

1.2 Opportunities and targets

EU Communities: the EEFE will catalyze the development of instruments and services that allow the identification and understanding of the generating mechanisms, of the interactions and feedbacks involved in the complex adaptive techno-economic-social systems, with attention to safety, mobility, energy, aging, fragility, resilience, contagious and avalanche effects, environmental compatibility, sustainable growth, and so on.

EU Society: the EEFE will help develop instruments and services that provide concrete exploitable support to policy makers, policy institutions and regulators, e.g., to evaluate R&D incentives, fiscal policies, regulatory policies, monetary policy, and so on.

EU Citizens: the EEFE will provide instruments and services that allow an effective and transparent dissemination of knowledge as well as efficient decision making procedures for the whole of Society in order to improve in particular electronic channels of citizenship and entrepreneurship, including e-participation, e-consultation, e-legislation, e-petition, e-deliberation, and so on.

2 Economic context and theoretical background

In the last thirty years, most of the advanced economies and of the developing countries have undertaken a profound transformation associated with the deregulation of financial markets, the liberalization of capital transfers, and in the privatization of the banking system. The process of deregulation and privatization has not been limited only to the financial sector but has also involved all the other sectors of the economy. This profound economic, political and cultural transformation can be probably traced back to 1971, when the post-World War II Bretton Woods system of fixed international exchange rates and dollar peg to gold was repealed by the Nixon Administration in the US. The process then acquired momentum in the early 80s, with the financial market deregulation promoted in US by the Reagan administration and in UK by the Thatcher government, and accelerated in Europe the late 80s and early 90s with the fall and the break up of the Communist bloc and the birth of the European single market.

On a smaller scale, Iceland can be regarded as a case study of the deregulation, privatization, and financialization process, which began there under the Oddson premiership in 1991, and that was characterized first by the privatization of the state-owned manufacturing system, mostly fish processing plants, accompanied by tax reduction and other business oriented reforms, and later by the privatization of the banking system in the early 2000s, which, within a deregulated environment, was allowed to grow and expand internationally, with a total balance sheet reaching a size close to ten times the Icelandic GDP. Outside the Western hemisphere, it is worth citing the program of economic reforms promoted in China since 1978 under the Deng Xiaoping leadership, that led China towards a market-like economy, and the adoption of a package of market-oriented reforms undertaken in India since 1991, which included deregulation, privatization, and tax reforms measures.

Since the late 80s, economic policy worldwide has thus been devoted to the implementation of the liberalization, deregulation and privatization agenda. Under the theoretical justification that globalization necessarily improved global welfare, a set of policies advocated by the so-called Washington Consensus, promoting free trade, capital mobility, and financial market deregulation, were implemented with particular emphasis in developing countries in South America and Asia.

The core of macro-economic modelling constituting the theoretical foundation of these economic developments is constituted by the so-called dynamic stochastic general equilibrium (DSGE) approach [7]. DSGE models include at least three kinds of representative agents: households, firms, and a central bank, while the financial/banking sector has been notoriously absent (except as a neutral channel of payment and the setting of interest rates). Households are supposed to maximize their (homogenous) utility, firms to maximize profits, and the network structures among the agents are considered as being irrelevant. The uncertainty of the future is modelled via the occurrence of random shocks affecting the economy. Such shocks may be inventions increasing productivity, bad weather decreasing it, and all sorts of other exogenous influences. The basic question addressed by the DSGE model is what strategies the central bank can use to maintain price stability and employment or, more generally, to enable the economic system to better absorb the exogenous shocks. In recent years, DSGE models have been considerably elaborated to address many other questions, e.g. how to deal with imbalances in global capital flows [8] or how to reduce greenhouse gas emissions [9].

However, it should be recalled that all these models are, as their name suggests, equilibrium models. It is taken as an article of faith that markets if temporarily out of equilibrium will return to equilibrium. As is well known since the 1970s, this assumption has no theoretical foundation. It was argued up till 2007 that the models were a good approximation for modelling the evolution of the economy. Nevertheless, the models contained no possibility of a crisis and it was simply assumed that markets and economies would "self organise" into an efficient state if essentially left alone.

Hence the financial crisis of 2007-2009 can be seen at best as a stress test for DSGE models and at worst a challenge to their validity. J.-C. Trichet, president of the European central bank, summarizes well the outcome of this test of (or challenge to) the DSGE models by pointing out that they "failed to predict the crisis and seemed incapable of explaining what was happening to the economy in a convincing manner", and "we need to better integrate the crucial role played by the financial system into our macroeconomic models" [10]. Adair Turner, Head of the U.K. Financial Services Authority (2010), summed the situation up by saying, "But there is also a strong belief, which I share, that bad or rather over-simplistic and overconfident economics helped create the crisis. There was a dominant conventional wisdom that markets were always rational and self-equilibrating" [11].

As Trichet himself recommended, other approaches, which were not equilibrium models nor based on omniscient agents with rational expectations, have been developed. In particular, multi-agent models have been proposed as a way to overcome these problems [12–15]. In these models, heterogeneous agents follow various decision rules, including optimization on the basis of limited information, but also imitation of others and random mutations of behaviour [16]. The network structure among agents is included as an important property and, in particular, a given agent may be able to observe only a subset of the other agents. With this approach, it has been possible to embody what Soros has referred to as the "reflexivity" of financial markets, to show how conventions that emerge in these markets can stabilize them, and how regime changes, including financial crises, can occur endogenously [17–28].

Moving beyond DSGE models to multi-agent models and other theoretical and computational approaches is a route that has to be explored, especially if the analysis is enriched by sound knowledge from economic history [10]. This opens a novel arena for research and study where different approaches to modelling and design can be studied, evaluated, tested, compared and cross-fertilized on the basis of transparent data and in an shared ex-ante context, as proposed in the European Economic and Financial Exploratory.

3 Scope and activities

In the current crisis (or we should rather say "in the most recent of the unending succession of crisis episodes" (see [29]), we are faced with a virtual collapse of the world's financial system, which had its seeds in the bursting of the real estate bubble, itself fuelled by accommodating monetary policy, which in turn was implemented to fight the negative impacts of the crash that bursts the dot-com bubble. These crises have dire consequences for the real economy, with many entangled consequences that are linking the United States to Europe and to China and Japan, just to mention the biggest players. The proposed explanations involve hidden systemic vulnerabilities resulting from interactions between the real and financial sides of the economy, networks of banks, the dynamics of trust and of contagion at all levels.

The European Economic and Financial Exploratory should address the global characteristics of the world economy as well as those of the different sectors and take account of the many dimensions and dynamical interactions between the various sectors and regions. In contrast with the central tenet of DSGE models that posit "market equilibrium" and homogeneity, the focus should be on enlarging the conceptual framework and the theoretical frameworks by borrowing from and merging many different disciplines to address the fundamental out-of-equilibrium dynamical heterogeneous many-dimensional nature of the economic and financial systems.

Among the possible actions on the economic area, the Exploratory will focus on:

A. Designing of innovative policy initiatives for the global economy and its markets;
B. Performing societal simulation to assess impacts of policy measures;
C. Developing new tools that identify emerging societal economic and financial trends using innovative approaches. It is here that the power of ICT is so important allowing us to gather, and analyse large amounts of data on various economic activities at a scale that was hitherto unattainable.

The Exploratory will deliver innovative and powerful ICT solutions for economic policy design and will substantially advance research in non-classical economic modelling, simulation techniques and process modelling, building on social networking and dynamics methodology techniques. The tools developed will exploit the vast collective data and knowledge resources of Europe's public and private sector and will build on lessons learnt from complex systems modeling, including those at urban or regional scale. More specifically, the activities are discussed in the following sections.

3.1 Extensive database and innovative metrics

For these purposes, on the empirical side, both developed and major emerging markets in the Americas, Europe and the Asia-Pacific region should be monitored in all their dimensions, with the aim of finding new indicators and combination therefore, in order to foster the development of new ideas, new questions and concepts and new models to address what is clearly a fundamental failure of standard Economic theory [30–32]. This includes:

- Equities: important or representative stocks, indices or sectors;
- Commodities: energy and fuels, base metals, precious metals, soft commodities and their representative futures and indices;
- Credit: corporate bonds, government bonds and their representative CDS spreads, indices and sectors, fiat money;
- Rates: yield curves, currency exchange rate pairs, swap rates, futures (e.g. bund, treasuries, etc.);
- Risk gauges: implied volatilities (e.g. VIX, VDAX, etc.), LIBOR-OIS spread, TED spread;
- Goods: Consumable, capital and durable goods (raw data, indices or sectors), inflation and consumption;
- Labour: unemployment, skills distribution, aging;

– Industrial production, productivity, manufacturing and inventories;
– GDP and GDP growth;
– Inflation (CPI, PPI) and consumption;
– Government debt, banks' and firms' leverages, insolvency bankruptcies;
– Current account and trade balances;
– Balance sheets: firms, banks, etc.
– Real estate prices (both private and commercial);
– Logistics/supply chains/material + money flows;
– Network of interactions: production supply chain, credit supply chain, financial supply chain.

It is worth remarking that the sources of data will be heterogeneous in terms of both formats and origins. As concerning formats, semantics web-based data gathering facilities with emphasis on data interoperability will be a key element for the design of the platforms and infrastructures. Moreover, both open-source and commercial services will be considered so as to ensure quality and timely availability of data. Indeed, these feature are essential pre-requisites in order to observe the state of the economy and to evaluate prodromes of crisis.

3.2 Assessing the short term needs of practitioners

It is essential to start from the needs of practitioners. There are three main reasons for this. First, the solutions and results proposed by the Exploratory should be useful, and this is most likely to happen if it takes the needs of practitioners as one of its starting points. Second, the Exploratory should help practitioners to explore new tools, theories and mindsets, and this will only happen if they perceive the project as being of obvious, practical use to them. Third, addressing the challenge posed by the financial crisis of 2007-2008 (which is still unravelling in a series of cascades) for economic modelling leads into areas of research where a tremendous number of possibilities can be explored. Taking into account the needs of practitioners provides some guidance in the face of all of these choices, and it can provide fruitful challenges and stimulation to researchers. Of course, this cuts both ways. The research should also challenge and stimulate practitioners to leave well-trodden paths from time to time and to be open to new patterns of analysis and inquiry.

3.3 Open debate among specialists with diverse views

A key challenge for decision-makers and researchers dealing with large-scale economic problems consists in the considerable communication barriers separating specialists with diverse views. The problem is not the diversity of views, not even the existence of serious disagreements on major issues, but the inability of nearly all relevant communities to engage in an open debate where the diversity of views is treated as an opportunity and a resource fostering new insights and better decisions. This is one of the keys to overcoming those barriers at key junctures and the Exploratory should constitute an arena where specialists with very different background can study, evaluate, test, and compare differences of views with the curiosity that takes advantage of different points of views to gain new insights. We expect that this kind of debate will lead to new ideas and insights that cannot and need not be defined in advance.

3.4 Advances in economic and financial modelling

We aspire to formulate a general micro-macro economic theory that considers general equilibrium structures only as special cases of a more general framework acknowledging that the real economy is an out-of-equilibrium changing complex systems with many coupled heterogeneous agents entangled in networks of networks with reflexive interactions [17,33–35]. In this contest, the micro- and macro- will fuse in a single vision that considers as reference cases the complex network structures formed by the agents in a social and out-of-equilibrium economic environment. Indeed this approach is already being taken up by the group working under Haldane at the Bank of England, [36]. This sort of approach allows one to model the risks of vulnerability with respect to financial crises, taking into account the dynamical nature of the erosion as well as recovery of conventions and trust. Furthermore, an important expected advance on the modelling is represented by the inclusion of features previously considered as being exogenous. As an example, Gabaix [37] has shown that if we take into account the size distribution of firms in the economy, we no longer need to assume, as has been done, that shocks to the economy are exogenous. Shocks to large firms can have an important impact on the whole economy, but keeping track of this distribution, which we shall do, is not part of the standard economics agenda. Similarly, Malevergne et al. [38] have shown that the standard Capital Asset Pricing Model (CAPM) should include another endogenous or intrinsic risk factor, in addition to the market portfolio, in order to account for the risk of lack of diversification resulting from the Zipf power law distribution of firm sizes. Malevergne et al. have quantified that there is no need for the phenomenological Fama-French three-factor model, once one accounts for the heterogeneity of firm sizes. It is worth remarking that this is a crucial objective in order to obtain endogenous financial-economic models.

Finally, the agent-based modelling approach will be employed to take into account the complex pattern of agents' behaviours and interactions that takes place in the credit and financial markets, such as network effects, credit rationing and bankruptcy waves, and herding behaviour. The structural aspects of the economy such as the leverage and the balance sheet inter-linkages of economic agents will be also fully taken into account by agent-based models. The usual criticism, that multi-agent models are cursed with so many parameters that it is all but impossible to test them against the data available, will be addressed by studying specific data-driven as well as policy-driven issues. This move to a more inductive rather than deductive approach is in line with other sciences. Indeed, the Exploratory aims to collect, store and process, borrowing from the vast reserves of Europe's private and public sectors collective data and knowledge resources.

3.5 Policy proposals for the governance and regulation of the globalized economy

One of the main objectives is to use the agent-based economic simulation frameworks and the related advancement in the understanding of the functioning of economic systems in order to design and test a complete set of policy proposals and reform actions for the globalized economy both in the international and in the European domains. What we believe is required both by regulators and policy makers are experimental environments for evaluating new regulatory and taxation regimes. This will help to find the sources of instability and those factors likely to mitigate them and devising aggregate risk measures that are able to alert regulators and participants of the potential of welfare destroying behaviour and interaction in certain forward-looking scenarios. For instance, the regulators would be interested in estimating the likelihood and the welfare costs of ex-ante diverse and distinct algorithms suddenly coordinating and synchronising.

This will capitalize on the main research results by FuturICT in order to empirically and theoretically support the validity of the policy proposals. The ICT framework and facility of the Exploratory should be able to simulate the economy according to different methodological approaches, from general equilibrium models to out-of-equilibrium agent-based models, enable the involved parties to test and validate the effects of the different policy measures in a wide spectrum of conditions. The policy proposals will aim to influence in a fruitful way three main contexts: (i) the economic domain, with a focus on macroeconomic stability and growth with appropriate fiscal and monetary policies, (ii) the environmental context, with a proper design of environmental policies, and (iii) the regulatory frameworks of financial and credit markets. Particular attention will be also devoted to policies aimed at preventing and mitigating the effects on the real economy of credit and financial crises, such as the crisis that started in 2007. In this respect, the investigation of the role of positive feedbacks and bidirectional relationships between the financial and the real sector of the economy will play a key role in the research performed at the Exploratory, with a focus towards the important concept of reflexivity, self-reinforcing mechanism, and dynamical interactions between heterogeneous economic agents.

4 Five prong action

The European Economic and Financial Exploratory (EEFE) will have five pillars that will be closely integrated:

1. Behavioral and decision making experimental facility;
2. Economic policy and regulation observatory;
3. Network-based crisis forecasting facility;
4. Financial crisis observatory;
5. Computational platform and data facility for economic and financial modelling.

These five pillars will be built on the strengths of existing centres in Europe that will serve as focus and organizing platforms for the European community:

I the research priority area Behavioral Economics (BE-UvA) at the University of Amsterdam (UvA) in which two research centers collaborate, the Center for Research in Experimental Economics and political Decision making (CREED) and the Center for Nonlinear Dynamics in Economics and Finance (CeNDEF), both at the University of Amsterdam (UvA),

II the UNIGE Centre for Interdisciplinary Research on Economics and Financial Engineering in Genoa,

III the project Forecasting Financial Crises (FOC) funded within FP7 of the EU within the FET OPEN Scheme, which is a consortium composed of the National Research Council of Italy (CNR), the Universit Politecnica delle Marche (UNIVPM), the ETH of Zurich (ETHZ), the City University of London (CITY), the University of Oxford (UOXF.MQ), Barcelona Medialab (BM), the European Central Bank (ECB), the Stefan Institute (SI), the Rudjer Boskovic Institute (RBI) and Eotvos University (ELTE),

IV the Financial Crisis Observatory at ETH Zurich and

V the Algorithmic Trading and Risk Platform at University College London.

We now explain and develop this five-prong approach in the next subsections. In order to help the reader get an easier access, we group important definitions in Appendix A.

4.1 Behavioral and decision making experimental facility

Context

We want to anchor our research and the resulting operations on a solid understanding of how individuals make choices and how they interact in social systems. While there is already a vast body of literature on the decision-making processes of human beings and on their psychology and behaviour particularly in economic contexts, we believe that there is still much more is to be learned and used by a continuous interaction process between laboratory experiments, models and implementations. This is the justification for our proposition to include a behavioral and decision making experimental facility within the exploratory of economics and finance.

The mainstream economics paradigm of homo economicus, characterized by rational behavior of a representative agent, is no longer valid in a complex, rapidly changing world and needs to be replaced by a paradigm of complex adaptive systems of interacting, heterogeneous and boundedly rational individuals. Behavioral economics and behavioral finance have started to develop an alternative behavioral theory for individual economic decision making under uncertainty. An important new methodological tool has been to test these behavioral theories in controlled laboratory experiments with paid human subjects. The Nobel Prize in Economic Sciences for Vernon Smith and Daniel Kahneman in 2002 shows that the role of psychology in economics as well as laboratory experiments as an empirical tool of testing theory have become widely recognized in the field.

The vision of the behavioral and decision making experimental facility is to build on the existing research within the research priority area Behavioral Economics (BE-UvA) at the University of Amsterdam in the Netherlands to develop a European know-how and facilities to test hypotheses on how human behavior and design of markets shape the emergent properties observed in economies and financial markets. Extending the current collaboration within BE-UvA, the behavioral and decision making experimental facility will perform laboratory experiments for complex economic systems to study both individual behavior at the micro level, the interactions of individual decision heuristics and the aggregate macro behavior resulting from these interactions. The Behavioral and decision making experimental facility aims to study micro and macro behavior in complex economic systems through controlled laboratory experiments, field experiments and large web experiments.

The behavioral and decision making experimental facility is naturally linked to the other pillars of the EEFE. As laboratory, field and web experiments, it will be extensively used to study economic policy and market regulation, the role of network structure in the spreading of financial-economic crises, and to study individual and group behavior and their role in the emergence of crises.

Main vision of behavioral and decision-making experimental facility

1. To facilitate the study of interactions of individual decisions under uncertainty and the resulting emergent group behavior in complex economic systems through controlled laboratory experiments, in real field experiments and in large computerized web experiments.
2. To test complex agent-based behavioral models in economics and finance by confronting agent-based models with experimental micro and macro data generated in the laboratory and in web and field experiments.
3. To serve as a laboratory for students, researchers, financial experts, policy makers and the general public.

Methodology

The behavioral and decision-making experimental facility will build on 4 complementary, but closely related methods of economic-financial research:

1. Agent-based modeling of complex economic and financial market systems;
2. Laboratory experiments in a controlled environment with paid human subjects;
3. Field experiments, through detailed questionnaires, interviews and data collection;
4. Large web experiments to test interactions of thousands of individuals and the resulting aggregate behavior in complex economic systems.

Agent-based models provide the theoretical framework that needs to be tested in laboratory, field and web experiments. Experimental economics has become a well-established field and laboratory experiments provide valuable tools to study human behavior in decision making under uncertainty in a controlled environment. Field experiments, to collect detailed data of individual consumers, firms, investors, etc. in real markets, e.g. through repeated questionnaires, interviews, etc., have been introduced more recently and form an additional, complementary tool to collect data about individual decisions and strategies. Large web experiments, where a computerized experiment is run through the web, are much more recent and only few web experiments have been done in economics and finance. Web experiments are an ideal, complementary tool to study interactions in complex systems consisting of many, say thousands of individuals interacting through markets, networks or other trading institutions.

We will also explore the full potential of the concepts that can be derived from "prediction markets", which are forums for trading contracts that yield payments based on the outcome of uncertain events [39]. We will analyze the potential for new forms of prediction markets to better understand how value added emerges from online collaboration tools, namely how people use them to produce relevant content. Our idea is to combine this research with education: since online collaborative tools are likely to become ubiquitous in the close future in public and corporate environments, we intend to meet the following goals: (i) be an interactive and playful introduction for stakeholders, (ii) explore the potential of online collaborative tools from a socio-economic perspective, and (iii) ensure scalability to ensure the best "wisdom of crowds". The potential for analyzing and measuring sentiment, confidence levels and other psychological variables is significant. This will spill-over to the understanding of social interactions and to the prediction of instabilities and crises.

Technology

The technology will be built on the existing research within the research priority area Behavioral Economics (BE-UvA) at the University of Amsterdam that combines two research centers, the Center for Research in Experimental Economics and political Decision making (CREED) and the Center for Nonlinear Dynamics in Economics and Finance (CeNDEF). CREED runs one of the best-equipped experimental economics laboratories of Europe. It consists of two laboratories and one reception room in which the subjects can be briefed before the experiment starts. One lab has 36 cubicles with desktop computers and the other one 24 cubicles with laptops (MacBooks). Both laboratories are connected to the same network and fileserver, which makes it possible to run market sessions with up to 60 participants. The MacBooks are also available for outdoor experiments using a wireless network. CeNDEF is one of the pioneering centers for complexity research in economics and finance combining complexity economics theory, agent-based simulation and empirical testing using laboratory experiments and empirical data.

Challenges and metrics of success

CeNDEF and CREED have already successfully studied individual interactions and market behavior in laboratory macro experiments [40]. In particular, it has been found that in markets with positive expectations feedback, as in financial markets where investor optimism reinforces an upward price trend, asset price fluctuations are unstable, exhibiting excess volatility and persistent deviations from fundamental market prices [41]. An important challenge for the behavioral and decision-making experimental facility is to perform systematic macro experiments on a larger scale in the laboratory, through field experiments and very large web experiments with interactions of up to thousands of individuals.

Experimental data on micro behavior and macro behavior will be gathered for different groups of individuals, including students, researchers, experts, policy makers and the general public. The role of experience, networks and information on the stability of large complex systems will also be studied [42–48].

Laboratory, field and web experiments will be employed to test agent-based complexity models and study the effect of network structure on aggregate behavior, the spreading of news through different network structures, the fragility and resilience of financial systems and the effect of market regulation in complex systems with interacting agent systems.

4.2 Economic and regulation policy observatory – ERPO

Context

The social sciences seek to understand not only how individuals behave but also how the interaction of many individuals leads to large-scale outcomes [49]. This has been admitted even by the most standard of macroeconomists, for as [50] said, "Applications of economic theory to market or group behaviour require assumptions about the mode of interaction among agents as well as about individual behaviour." Thus, understanding an economic and financial system requires more than an understanding of the individuals that comprise the system. It also requires understanding how the individuals interact with each other, and how the macroscopic regularities arise out of the decentralized local interactions of heterogeneous, autonomous agents [49]. In terms of models designed for policy advice we need to develop models that follow a fundamentally different approach from the dynamic stochastic general equilibrium models (DSGE) which are currently employed by the European Central Bank (ECB) or the European Commission on Economic and Financial Affairs (ECFIN). These models are typically not rich enough to capture the reality and complexity of real economies in terms of their spatial structure, heterogeneity of firms and households, and institutional details explicitly modelled. For example, the ECFIN model on which many of the policy recommendations of the European Commission are based, has only two countries and three sectors. It lacks a more appropriate spatial dimension and differentiated skills of workers just to name two features [51]. The research objectives of this first pillar are to analyze, model and solve economic and financial problems through a multidisciplinary approach that involves competences originally developed in economics, engineering, computer science, mathematics and physics.

Main vision for the observatory on economic and regulatory policy

The primary objectives are

1. To provide a real answer to the research programme on a Generative Social Science (see [52]), which seeks to explain socio-economic phenomena by constructing artificial societies that grow explanations from the bottom-up. In particular to provide an innovative, effective and usable tools for approaching macroeconomic

modelling and economic policy design questions (see FP6 project EURACE and FP7 project CRISIS);
2. To generate an agent-based platform that integrates different models, sectors and markets (in particular, goods markets, labour markets, financial markets and credit markets) calibrated on economic data. This objective includes the demonstration that the developed platform can be fruitfully applied to the analysis of relevant policy questions and to the exploration of scalability of large economic models;
3. To serve as facility for what-if analysis, scenario evaluations and computational experiments focussed on policy, market and regulation design.

The economic and regulatory policy observatory – ERPO within the EEFE – will be a scientific platform (infrastructure, data, services and facilities) focussed on massive, scrupulously accurate (both scientifical and technological), quantitative and methodical analysis and testing of the hypotheses, constraints and limits of policy and regulations. ERPO should become a reference, free and independent voice to the European and International community so as to inform and, above all, offer independent analysis of facts and information in economics and finance. A embryonic version for this ERPO can be found in the European Project EURACE, launched in 2006 and coordinated by the University of Genoa [15, 53–61]. An economic and regulatory policy observatory that is relevant with respect to globalized dimension of the economy must therefore monitor and understand the local economic variables as well as the global markets and the global economy in closed connection with the other four pillars of EEFE, so to evaluate risk and to foresee and stabilize crises.

The ERPO within the EEFE staffed by social and computer scientists and engineers will be open to visitors for collaborations, seminars, theory and model testing. It will also have the mission to communicate results to stakeholders, private sector, policy makers, regulators, research community, media and the general public with the goals:

- To inform and educate by promoting and disseminating innovative theory, models and methodologies;
- To disseminate as widely as possible all the results;
- To alert when signs of increased risk and policy effects are found;
- To advise by elaborating recommendations that may decrease risk and help to stabilize the economy.

Finally, the ERPO within the EEFE will work out procedures to guarantee its compliance with the highest ethical standards. The services should be transparent, accessible without any prejudice and with the ambition to be competent in topics, provocative in critics, and effective in proposals. In agreement with the fiduciary principle, members of the ERPO should not use the output of their analysis for personal account trading before the disclosure of the results.

Methodology

There will be neither boundaries nor limit to the methodologies employed. In addition to the more standard approaches of traditional economic modelling, the reference methodologies will include agent-based computational economics models, techniques and methods from statistical physics and complex adaptive systems. Many different distinctive features should be included:

- The inclusion into the financial-economy model of features previously considered as being exogenous (i.e., the closure of the system with a fully-specified models of

a complete economy that explicitly specify all real and financial stocks and flows and allow to aggregate upward from the micro-specifications to the macroeconomic variables of interest);
- The encompassing types of real and financial markets and economic agents;
- The wide use of empirically documented behavioural rules;
- The different levels of time and space granularity. It is possible to investigate the impact of real-life granularity on the economic outcomes, and to analyse the consequences of a modification of this granularity;
- The asynchronous decision-making across different agents;
- The explicit spatial structure, allowing to take into account not only regional and land-use aspects, but also more generally the fact that all human activities are localized in geographical and/or network space;
- The evolving social network structure linking the different economic agents and institutions;
- The large number of agents, allowing to discover emerging phenomena and/or rare events that would not occur with a smaller population;
- The analysis of economic, financial and social data;
- The analysis of financial data stored in ICT environments (Queries, Blogs) [62–65];
- The calibration on European economic data and the focus on European policy analysis.

The different types of models will be integrated in a framework with the objective of computational efficiency, transparent scalability and interoperability. It will be designed on the basis of the specific cases that emerge from the interaction with practitioners and the results composed by a multi-scale modelling architecture. The aim is to allow decision-makers, practitioners, scholars and students to run, couple and compare different economic models of real, credit and financial sectors as well as to the economy as a whole.

Technology

Computer science and engineering play a major role in the development of the tools and platform for ERPO within EEFE. This involves both hardware and software and should take as a basis successful small scale examples (generally speaking developed within the EU funding system) so as to move to a level where one can deal with questions and challenges at a scale of the globalized economy and its markets. The community should start from state-of-the-art solutions in the area of agent-based and complex system simulators and provide a breakthrough through formal and flexible solutions specifically designed for transparent use of high performance computing. It is expected that ERPO implements and shares a new kind of European Platforms for huge distributed databases and distributed computational clusters implementing new methods for economics and finance.

The existing software should be integrated with a specific emphasis on interoperability of the (economic and finance) model modules. The ERPO within EEFE should face data explosion problems by computational networks that should be able to cope with peta-bytes of heterogeneous data, to simulate systems with billions of agents, to provide tools to analyze the resulting data. The huge dimension of data and agents (in order to address both real data and process mining for economic and institutional analyses and synthetic explorations for data driven simulations as well as what-if computational experiments) plays a major role. Three different kinds of solutions will be considered: a personal computer, a private cluster and a HPC service. The first one should respond to user-driven curiosity and ensures the necessary elements to guarantee transparency and accessibility without any prejudice. The second one should respond to research questions and should guarantee to stakeholders, policy makers, regulators, and research community the possibility to address some real scale questions. The latter one should be a key feature of the ERPO that allows one to serve as a facility for what-if analyses, scenario evaluations and computational experiments focused on policy, market and regulation design. In this case, the mission is to address major real scale questions and to communicate results to stakeholders, private sector, policy makers, regulators, research community, media and the general public.

Challenges and metrics of success

The ERPO within the EEFE will operate at a high conceptual level and, since it is free of profit and politics motives, will allow us to objectively observe and analyse the global economy and its markets. It formulates a general micro-macro economic theory that considers general equilibrium structures only as special cases of a more general framework acknowledging that the real economy is an out-of-equilibrium changing complex systems with many coupled heterogeneous agents entangled in networks of networks with reflexive interactions.

This will enable us to get over the inability of nearly all relevant communities to engage in an open debate. The new approach treats the diversity of views as an opportunity and a resource fostering new insights and better decisions in economics and finance. In this contest, the micro- and macro- will fuse in a single vision that considers as reference cases the complex network structures formed by the agents in a social and out-of-equilibrium economic environment. This will enable us to model the risks of vulnerability with respect to financial crises, taking into account the dynamical nature of the erosion as well as recovery of conventions and trust. All this elements are crucial to address the current crisis; we are faced with a virtual collapse of the world's financial system (originated by a bubble in real estate, itself fuelled by monetary and regulatory responses to alleviate the aftermath of the collapse of previous bubbles), which has had dire consequences for the real economy. The explanations provided involve interaction between the real and financial sides of the economy, networks of banks, trust and contagion at all levels.

The data observatory will provide and understanding of the mechanisms, behaviours and interactions that take place in the credit and financial markets, such as networks effects, credit rationing and bankruptcy waves, and herding phenomena. The structural aspects of the economy such as the leverage and the balance sheet inter-linkages of economic agents will be also fully taken into account by agent-based models. The problem, that multi-agent models are cursed with so many parameters that it is all but impossible to test them against the data available, will be addressed by studying specific data-driven as well as policy-driven questions and computational experiments. Indeed, by borrowing from the vast reserves of Europe's public sector, the ERPO within EEFE aims to collect, store and process collective data and knowledge resources.

A European Union-sponsored EPRE, then, will fill a void both in the academic and the policy making world by creating two specific resources: a storehouse of useful global data (for in-house use) and a monitor of the global economy. It is worth remarking that, as opposed to finance, real and credit data are not globally accessible as these data (which are the property of statistical institutions, central banks and treasury ministries) are made available usually only at an aggregate level. This severely reduces the possibility of understanding the real state of the economy and to offer independent analysis of facts and information in economics and finance. Moreover, it results in a limited possibility to evaluate the effect of policy and regulatory decisions that have a major impact on the economy and society as a whole. In this respect, the ERPO within EEFE will offer a reference, free and independent voice thus enabling the participation of citizens.

Finally, the ERPO will offer regulators and policy makers an economic, computational, experimental framework in order to design and test a complete set of policy proposals and reform actions for the globalized economy both in the international and in the European domain. The ICT framework and facility of the ERPO will be able to simulate the economy according to different methodological approaches so as to test and validate the effects of the different policy measures in a wide spectrum of conditions. The policy proposals will aim at having a positive impact in three main contexts: the economic domain (with a focus on macroeconomic stability and growth with appropriate fiscal and monetary policies), the environmental context (helping to design effective environmental policies) and the regulatory frameworks of financial and credit markets. Particular attention will be also devoted to policies aimed at preventing and mitigating the effects on the real economy of credit and financial crises, such as the one that developed in 2007-2008. In this respect, the investigation of positive feedbacks and bidirectional relationships between the financial and the real sector of the economy will play a key role in our research, with a focus on the important concept of reflexivity, self-reinforcing mechanism, interactions in economics.

4.3 Network-based crisis forecasting facility

Context

This pillar mostly addresses the problem of the assessment of infrastructural fragility in financial and economic systems. This is a problem that can be solved only by a cross-boundary multidisciplinary approach where competences from Computer Science to Statistical Physics are needed to complement the standard approach of Economics. Thanks to the methodology and ideas of Complex Networks, this pillar will offer a theoretical and algorithmic framework to measure quantitatively the robustness of financial institutions and actors. By means of network modeling, we also aim at describing the possible future evolution of the system considered. This would allow the simulation of plausible future scenarios, with respect to policy decisions and actions. As a final product of this research, we want to provide a technological platform where macroscopic indicators are shown, and computer-based simulations can be realized.

Main vision for the network-based crisis forecasting facility

There is a now a large consensus which asserts that our current theoretical and technical tools are inadequate to understand, forecast and mitigate financial crises. The European Central Bank (ECB) has recognized that the tools currently at the disposal of policy makers to monitor financial systems are insufficient to cope with systemic risk. The ECB has called officially for (1) more integrated information systems, (2) a systemic approach that takes into account the network of financial exposures, and (3) new appropriate systemic risk indicators [66].

As a response to the demand from policy makers for new tools to monitor financial instability, our vision is that progress in this direction cannot be achieved by remaining restricted to the modeling approaches of financial economics alone. A new approach including in addition the methods and insights from the theory of complex networks, as they are used and developed in physics and computer science, is needed in order to meet this demand. Indeed, the main problem with the current monitoring systems is that they are based on the idea that micro and macro behavior are of the same nature. First, crises are expected to require aggregate shocks, while in reality small local shocks can also trigger large systemic effects (e.g. the subprime market represented only a small fraction of the global credit market and yet started a global crisis). Second, "the traditional approach to financial regulation rests on identifying solvency with capital. In particular, solvency regulation has come up short in ensuring stability of the financial system" [67,68]). The case of Bear Stearns is an example of a default that occurred even though "it had a capital cushion well above what is required to meet supervisory standards calculated using the Basel II standard" [69]. Regulators have to face the fact that, in many situations, actions that ensure the soundness of one institution (e.g., solvability, liquidity capacity, etc.) may not be consistent with ensuring the soundness of another [70]. Local shocks can have systemic repercussions and the requirement to have sounder individuals can have the counter-intuitive effect to make the whole system more fragile. Again focusing on the system is more important than focusing on its component parts and in this context, the network-based forecasting of financial crises view the financial and economic system as a network of mutual exposures among institutions. To this aim, the computer-based programs developed through the network-based forecasting of financial crises will be integrated with data analysis on a computer platform laboratory with specific emphasis on systemic risk. This will allow a variety of agencies, public and private, to count on a unique representation of the economic and social phenomena and their interdependencies.

Incidentally, this will promote the formation of a new interdisciplinary community composed of sociologists, economists, political scientists, statistical physicists, computer scientists and engineers by allowing researchers to cooperate in investigations of specific topics, such as:

(i) monitor and evaluate real-time status of the economies of countries in their different macro components;
(ii) use, extend and develop a variety of methods including data mining, network theory, artificial intelligence, calculation of the community, complementing more established techniques of analysis;
(iii) provide the framework and infrastructure to perform analysis on the consequences of policies, assessments scenario and realize computational experiments to inform decision makers and help improve the quality of decision making underlying the policy decisions.

Methodology

As the current situation testifies, there is no accepted and working plan to react to global financial crises. For this reason, the preliminary assessment of fragility of these financial systems and possibly a forecasting of the precursors of the crisis can have a dramatic impact on the possibility to recover from financial downturns. Present models and technologies are inadequate for the mitigation of the consequences and only partially working in their forecasting. This has been acknowledged by the same regulators [66]. Following the indications of this report we want to go towards a system where all sources of information (especially the unconventional ones as that we can obtain from ICT networks as query-logs, blogs, twitter data), are integrated. We want to explicitly take into consideration the network structure, we want to define, on the basis of this new mathematics introduced, novel systemic risk indicators. In more details, the various lines of research are listed here:

1. We want to use the knowledge on failure cascades and contagion developed in the field of epidemics and complex networks [71] and apply these ideas to the case of financial contagion. In the same spirit, we want to explicitly stress that endogenous little shocks can have a global impact on the economy, contrary to the common view in economics, but similarly to what happens in Self-Organised Criticality.
2. We need to overcome the traditional micro vs macro approach, by considering at a mesoscopic scale the economy as a network of networks aggregating different financial actors into similar sectors.
3. We will adopt the network science and use quantitatively the predictions obtained with this methodology. In particular, the use of network theory can clarify one important issue. Contrarily to the common belief, increasing the number of links does not make the economy more stable. On the contrary, financial integration may increase systemic risk [72–77].
4. We will create a new consolidate database of financial data, formed by macroscopic indicators. Networks of correlations between financial institutions, networks of exposure with respect to Central Banks, (we also aim to reconstruct data from limited information to create a global network of exposures) and ICT data as Twitter and query-logs.

All this activity will be realized by a series of IT based devices. Firstly by means of Computer Models, based on Network evolution and Agent Based models we will be able to create plausible scenarios for the future evolution of the system, the possibility of concomitantly test the effect of policy actions. For example what happens by varying the rate of interest or saving specific institutions and not others, facilitating trade, and so on. We acknowledge that the final evaluation of these arguments is in the hands of politicians, namely it should represent collective societal preferences, but these tools can certainly help their decisions, by providing quantitative results in a short time. In all these activities, we shall proceed through continuous feedback from data analysis models, validation of models and visualization of results back to the data analysis. To give an example, we can monitor how financial distress in a bank (based the loss of asset value) can cause similar problems to other banks given the presence of a network of networks of correlations between these institutions. Another example is the use of networks to characterize the trade between nations. The results of network analysis allow one to define new metrics (indicators statistics) that can quantitatively characterize the competitiveness (fitness) of a country compared to the diversification and quality of products it exports. The description of product can be made to varying degrees of specialization ranging from individual products to industries. This new original approach defines quantitatively concepts that have so far been described only at the qualitative level.

Technology

Global issues such as systemic financial risk as well as others like climate change and pollution have the nature of social dilemmas. We believe that in the long run they can only be tackled with ICT and in particular, those ICT that exploit the collaborative aspects of knowledge sharing and action coordination. Our monitoring platform will be an example of a collaborative environment open to the research community aimed at the observation and control of a complex socio-economic system. The development of this platform will confront us with challenges that have a wider scope than the current project alone. In relation to this, we already witness in the present Information Technology society an impressive series of methods to track down, visualize and analyze the development of dynamical processes involving the well being of society. A major example of this activity is given by the recent studies carried out on epidemic spreading of diseases like the recent swine flu. Thanks to recent developments in the theory of complex networks [78,79], it has recently been understood that the topology of both transportation networks and social relationship affect dramatically the outbreak of the infection. Based on these studies, various group in the world have run simulations of likely scenarios for epidemic outbreak (i.e., the work of the group of Vespignani at Indiana University (`www.gleamviz.org`) and that of the "Research On Complex Systems" Group in Northwestern University (rocs.northwestern.edu)). By continuously recalibrating the models of diffusion with the real data (mobility of people, strength of the virus, velocity of infection in a context of transportation long distance world-flights and social interaction between people) the forecast becomes more and more accurate allowing authorities to take the necessary measures. These examples are particularly interesting and inspiring for the case of financial crises.

Challenges and metrics of success

Policy makers would like to know which regulations are more effective to prevent the spread of crises. It is therefore crucial to increase our capacity to anticipate the onset of systemic crises in order to examine future scenarios and evaluate risks. The concrete goal of this proposal is to develop a device for policy makers that: (i) signals the possible occurrence of a crisis; (ii) provides insights for the adoption of the appropriate policy measures; and (iii) allows one to evaluate future scenarios for each chosen policy. This is a very general problem and in principle the results of this activity can be extended in the future to other domains of application. The development of a framework for a computational forecasting infrastructure must necessarily combine modeling financial networks with empirical analysis and validation of the models.

The criteria for the success are related to the ability to effectively provide the expected major breakthroughs, i.e.,

1. a theoretical framework to measure systemic risk in global financial market and financial networks;
2. an ICT collaborative platform for monitoring global systemic risk;
3. algorithms and models to forecast and visualize interactively possible future scenarios.

We are conscious and know that the challenges are very ambitious and we are aware of the risks and difficulties in the development of such a computational forecasting framework. For this reason, the activities include both empirical and modeling tasks with a tight cooperation with the other pillars of EEFE as well as with experts in econometrics, forecast technologies and credit networks in order to validate the results obtained.

4.4 Financial crisis observatory – FCO

Context

In the past decades, capital flows have become increasingly global and to some extent autonomous with respect to the actual performance of economies. The financial component of economies has grown so much as to be referred to as the tail that wags the dog. Not unrelated, a fundamental cause of the unfolding financial and economic crisis is the accumulation of several bubbles and their interplay and mutual reinforcement that has led to an illusion of a "perpetual money machine" [4,5], allowing financial institutions to extract wealth from an unsustainable artificial process. Taking account of this diagnosis, we conjecture that many of the interventions to address the so-called liquidity crisis and to encourage more consumption are ill advised and even dangerous, given that precautionary reserves were not accumulated in the "good times" but that huge liabilities were. The most "interesting" present times constitute unique opportunities but also constitute a great challenge to develop innovative directions of research for practical solutions.

Main vision for the FCO

The primary objectives are

1. To identify current and forecasting future financial and economic risks or instabilities, including looming systemic risks, by analyzing in an integrated manner the time series of financial, economic as well as balance-sheet indicators for tens of thousands of assets around the world, on a daily basis;
2. To serve as a global destination for scientists and policy makers to collaborate, to test ideas and to compare theories in real time in a supportive competitive environment;
3. To support the first two objectives by creating a storehouse of useful, global economic and financial data.

There will be neither boundaries nor limits to the methodologies employed. The arsenal of the FCO within the EEFE will include proven and novel econometric techniques and methods from statistical physics and complex adaptive systems. As sources of useful concepts and tools, it also will draw on evolutionary biology, ecology, climate dynamics and other disciplines in the natural sciences, and on the mathematical tools developed in network theory.

The Financial Crisis Observatory (FCO) within the EEFE will be a scientific platform aimed at testing and quantifying rigorously, and systematically way and on a large scale the hypothesis that financial markets exhibit a degree of inefficiency [80] and a potential for predictability, especially during regimes when bubbles develop. The definition of a bubble is still very controversial and the question "should we burst a bubble and when" remains without an answer. A nucleus for this FCO is the initiative launched in August 2008 at ETH Zurich [4,5,81–85]. A Financial Crisis Observatory that is relevant with respect to increasing international linkages must therefore monitor the local financial and economic variables as well as the global markets and the global economy. For that purpose, both developed and major emerging markets in the Americas, Europe and the Asia-Pacific region will be monitored. For the FCO within the EEFE, we envision an observation room where, for instance, each of many computer monitors is dedicated to, say, "Risks of systemic crisis in South America" or "Risk of large market falls in Asia". A family of monitors would be devoted to Europe, one to Asia, one to the Americas, etc., where each monitor in a family shows the real-time analysis of competing (in the scientific sense) theories.

With respect to the monitoring of data and delivery of relevant information, we have taken as our inspiration, similar monitoring of activity and forecasts in seismology (e.g., `www.geonet.org.nz`) and space weather (e.g., `www.swpc.noaa.gov`), to name just two. With respect to the development of a platform where models compete on well-defined goals, we refer to the Collaboratory for the Study of Earthquake Predictability (CSEP, `www.cseptesting.org`), which is developing a virtual, distributed laboratory—a collaboratory—that can support a wide range of scientific prediction experiments in multiple regional or global natural laboratories.

Both for earthquake prediction and for financial crisis forecasts, scientific integrity and ethics are essential. For earthquakes, a prediction in a populated area may, for instance, lead insurance companies to stop offering insurance earthquake policies. Therefore, ex-ante scientific predictions require a rigorous framework that ensures sufficient communication between scientists who can work freely in their tests, while at the same time being isolated from the pressure of the media and of the public. For financial markets, predictions can have in addition the unwanted property of acting as self-fulfilling prophecies. The Financial Bubble Experiment at ETH Zurich has been conceived precisely to avoid such problem, in addition to providing a rigorous set-up for scientific experimentation of a theory of financial bubbles [4,5,82–85]. We will work on the ethical and operational issues associated with forecasting financial crises, to find efficient ways to communicate the findings to the scientific community and to the policy makers, while being responsible to avoid the potential misuse as well as the unwanted reflexive feedbacks.

The proposed FCO within the EEFE aims similarly to provide answers to the questions: (1) How should scientific prediction experiments be conducted and evaluated in economics and finance? (2) What is the intrinsic predictability of financial and economic systems? (3) How can the predictions be used for the development of macro-prudential early warning systems? Similarly to the CSEP endeavour, a major focus of the European FCO is to develop international collaborations among the regional European testing centres and to accommodate a wide-ranging set of prediction experiments involving geographically distributed economic systems in different social-cultural-economic-geographic environments.

The FCO within the EEFE staffed by scientists and data 'archivists' will be open to visitors for collaborations, seminars and theory testing, in the same spirit as that of the Newton Institute in Cambridge, UK (`www.newton.ac.uk`) or the Santa Fe Institute in Santa Fe, New Mexico, USA (`www.santafe.edu`). With this activity, it will also have as its mission to communicate results to policy makers such as regulators, the research community, the media and the general public with the goals:

- To instruct by promoting and illuminating new technologies and methodologies;
- To inform by distributing all the results;
- To alert when signs of increased risk are found;
- To advise by elaborating recommendations that may decrease risk or stabilize the system.

Finally, the FCO within the EEFE will work out procedures to guarantee its compliance with the highest ethical standards, to be transparent and to pursue the general interest. In agreement with the fiduciary principle, members of the EFCO should not use the output of their analysis for personal account trading before the disclosure of the results.

Methodology

It is well known and has been documented for more than a century that financial time series do not follow a Gaussian random walk process. Returns tend to have fat-tailed distributions, long-range dependence and volatility clustering in time, and there are asymmetries such as the leverage effect where large negative returns tend to precede higher volatility. Additionally, there is the existence of bubbles. Finally, there are crises, when market prices fall persistently, leading to cumulative losses that can reach globally to trillions of euros, and which are sometimes followed by economic recessions and/or depressions. The costs for afflicted countries that go into debt in order to stimulate their economies is typically of the order of 50-90% of a given country's annual GDP. The big questions that everybody would like to solve are: What are the determinants of crises? Can crises be forecast? With what lead time?

Can crises be avoided with sufficient early warning and/or by a suitable understanding of their generating processes?

A promising hypothesis is that crises often (always?) follow the development of financial bubbles. One of the tasks of the FCO will be to test this hypothesis and characterize empirically and quantitatively the different types of crises. Another important related task of the FCO will be to study, diagnose and possibly predict the end of bubbles. One of the promising meta-models of bubbles considers them as caused by collective behaviour or herding, which tends to generate positive feedback mechanisms that may result in a disconnection between the intrinsic (or fundamental) value and the actual financial price of an asset. Such bubbles may fuel financial and economic instability and may result in a change of regime or even a market crash that is sometimes followed by severe economic downturns. The way in which individuals can come to have a common but erroneous view has already been treated in the literature on learning, for instance in the belief in sunspots (see [86]), but we aim to pursue this in greater depth by enriching the concept with the exploration of endogenous mechanisms and not only exogenous processes.

Part of the core business of the FCO will be the identification of bubbles in real time. The FCO at ETH Zurich is already using models of bubbles developed and tested in Prof. Sornette's group in collaboration with international colleagues in Europe, US, China and Japan. The FCO within the EEFE will considerably enlarge the set of models and of statistical methodologies, building on the diversity of the different European researchers involved. Aiming at the diagnosis of bubbles and the prediction of crises, the FCO within the EEFE will analyse the financial and economic data on different time scales from tick by tick, to daily to monthly time scales. Additionally, a broad set of tools will be applied to capture non-Gaussian properties of the data that may be indicative of increased systemic risk (such as increased volatility, long memory or dependencies (see [87]).

As a prototype of the envisioned EFCO, the FCO at ETH Zurich already provides significant experience, with theories and techniques developed over the last 15 years and implemented in their current format at ETH Zurich since 2008. The FCO at ETH Zurich searches for precursory behaviours in the global financial system that may be indicative of an imminent correction with a possible destabilizing effect on the financial markets and/or the general economic system. The used methods are built on a successful interdisciplinary approach combining ideas from statistical physics, complex systems, human psychology and economics. The FCO at ETH Zurich has already successfully forecast ex-ante major bubbles and crashes in key systemic indicators, including commodities prices and major indices [4,5,82–85]. One can therefore be reasonably optimistic about the successes that would be provided by a pan-European effort building on the diverse and complementary strengths of the European researchers from many different disciplines.

Technology

The combination of software and hardware needed for such a FCO within the EEFE already has been implemented successfully on a smaller scale at the existing FCO of ETH Zurich. We have the experience and knowledge for the necessary expansion of this operational unit to the larger scale implied by the Flagship proposal.

The existing software has been developed over the past 4 years and is currently operational at a level of analysis of over two thousand global assets each day. The software is written in a combination of modern, high-level open source languages, optimized where necessary with low-level open source languages, and is portable among many types of clusters, machines and processors. That is, this software is fast, tested and robust and does not require specialized, expensive hardware. This existing platform will be combined with the UCL Algorithmic Trading and Risk Platform described in the next subsection.

Let us briefly describe the core infrastructure of the FCO of ETH Zurich, as it can be used as a template for the larger-scale ambitious FCO within the EEFE. Three types of hardware are used: personal computers and laptops (for quick, interactive analysis), a private rack mounted cluster of 5 nodes, each containing 4 quad-core processors (total of 80 cores for medium-sized analysis jobs and much post-processing) and the ETH Zurich Brutus cluster. The FCO at ETH Zurich is the largest single shareholder of Brutus, having purchased over 12% of the processing power of this shared-resource cluster of more than 10,000 cores. Brutus is used for the main, daily scans and analyses of over two thousand global assets. The private cluster and Brutus have been designed with large memory and disk storage, high speed internal networking and daily RAID data backup.

The limits of Brutus have not yet been reached. Scaling up an order of magnitude from two thousand to twenty thousand daily assets is, perhaps, just on the borderline of being practical within the existing Brutus shareholder model through a combination of modest hardware expansion and selected code optimization and/or re-writing. Our estimated goals for the FCO within the EEFE include more than twenty thousand daily time series as well as intraday analyses not presently made on Brutus. Further, other economic indicators beyond price time series are fundamental to study. Together, all of these factors are motivation for increased computational resources in close collaboration with the UCL group and other European researchers.

Challenges and metrics of success

The FCO within the EEFE will be truly unique in the financial world, where the usual primary mission is to maximize profit and the use of observations is aimed at finding valuable trading opportunities without regard to ripple effects beyond the balance sheet at hand. Also, it is different from the normal academic approach, which mainly relies (too strongly) on post-mortem empirical analyses and on unrealistic, theoretical models that do not capture actual market and economic dynamics.

In contrast, the FCO, operating at a higher conceptual level, will make meta-observations, in the sense that not being driven by a profit motive we can observe and analyse correlations among activities in the many global markets that will lead to better understanding of real, working markets without the shackles of seeking profit or supporting pet theories enshrined by decades of cultural biases. The global financial market is, scientifically speaking, a complex system and enough evidence exists to support the notion that more observations of the system are required to better understand it.

This is not the idea of ‘stamp collecting’ and cataloguing as much data as possible, only to store it in archives that are never used. Instead, it is the idea that careful, measured observations of the orbital periods of the sun, moon and Earth were necessary to discover Newton’s laws and the basis of modern science; that observations of many generations of plants were necessary to understand the basics of genetics; that countless observations of fossils and Galapagos turtles and birds were necessary to understand evolution.

In that context, it is striking that the history of global financial markets is scattered with major crashes and instabilities but, while there are many descriptions and explanations (see for example [88]), ex-ante forecasts of them and ex-post consensus explanations of them are lacking. The lack of understanding is due to lack of observations or, more specifically, the lack of rigorous systematic empirical recording of evidence. Most studies concentrate on a single 'representative' index (such as the S&P 500). As practitioners in this field, we realize that many such studies limit themselves to small data sets because finding multiple, comparison data sets is difficult. Yes, one could study every stock in the US; such data can be found relatively easily. But the US does not exist in its own bubble, so to speak. It is linked to Europe, to Asia, to the 'other' Americas. Finding data from those markets is still possible but is much more difficult and is usually costly, as academic budgets must buy commercial products that are priced for private financial institutions.

A European Union-sponsored FCO, then, will fill a void in the academic world by creating two specific resources: a storehouse of useful global data (for in-house use) and live monitors of global financial instability risk. One can easily picture such an online storehouse. Simply go to Yahoo! Finance (finance.yahoo.com) or Google Finance (`www.google.com/finance`) to see much free data of assets, indices and foreign exchange for many of the major countries. The FCO will expand this to as many countries and asset classes as possible, because of the guiding scientific idea that all markets are linked and representative observations from any given country are a priori as valuable as observations from a 'standard' country. After all, much of investment funding in emerging markets originates in such standard countries, hence disturbances in the remote country will have important effects in the original country.

The heart of the FCO, though, is based on the fact that markets are by nature fast-paced, ever-changing competitive environments. The study of them is much less so. Let us put experts to the test to see if they (and we) can compete in their own market, to see if they really have learned from the systems that they observe. What better way to study the competitive markets than by a 'friendly' scientific competition in which scientists from around the world set up live, real-time experiments and watch the results unfold together? Be it Darwinian evolution or the free market, the successful will survive and all will benefit. No longer will experts simply argue about past events. Instead, experts will stake their reputations on making careful forecasts instead of long-winded theories of the past whose value for the future remain untested. Two of many possible outcomes could be: reinforcement of the view that such forecasts in markets are inherently impossible or successful ex-ante forecasts of impending crises. Of course, we lean towards this latter view and understand that, if successful, such results would lead to the similarly difficult task of deciding what should be done at a policy level.

Key to the above is the definition of a "successful forecast". It is a relative concept that depends on the requirements and use to which it can be applied. Predicting global climate change, for instance, is not relevant to airplane route optimization at the time scale of days. Both time scales and precision are significant variables that contribute to what is called a successful forecast. This explains why the design of the FCO is to include practical implementations of forecasts, ranging from dynamical financial risk management to policy making alongside researchers. The observations are the data that will guide and help test the more important deliverables of new theories and forecasts of economic and financial risks, instabilities and crises.

4.5 European economic and financial exploratory platform & infrastructure

Context

Central to the success of FuturICT is the software engineering architecture of the Living Earth Simulator, Planetary Nervous System, Global Participatory Platform and Innovation Accelerator. The EEFE Platform & Infrastructure will develop the software architecture of the proposed European Economic and Financial Exploratory;

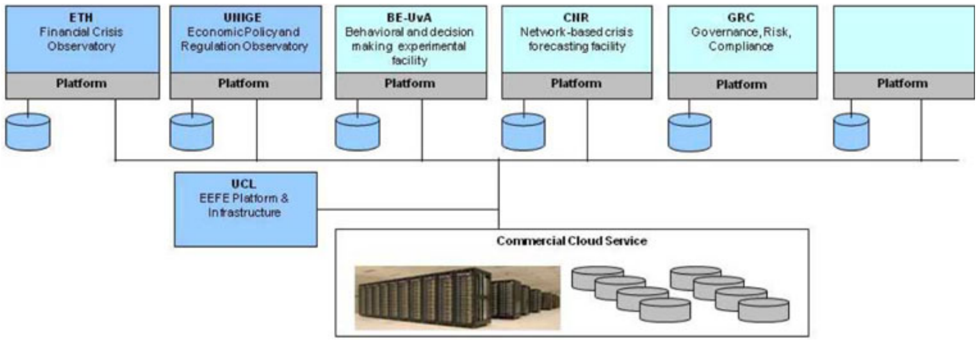

Fig. 1. EEFE infrastructure strategy.

contributing significantly to understanding how to build the Living Earth Simulator, Planetary Nervous System, Global Participatory Platform and Innovation Accelerator. Specifically the EEFE will provide common financial/economics platforms for collaborative experimentation of how complex financial systems behave and how to integrate knowledge across disciplines for the EEFE project Partners. The EEFE Platforms & Infrastructures will support individual modelling on Big data sets and also collaborative modelling across observatories.

Main vision for the European economic and financial exploratory platform & infrastructure

This fifth pillar of the EEFE will be focussed on the development of the EEFE Platform & Infrastructure. We envision that several centres in Europe will share resources, competence and platforms for mutual fertilization. This will ensure a common sharing of services via excellent delocalized centres that will support the financial and economic community for the research described in the preceding sections. These developments will benefit from continuous interactions and feedbacks between the developers and the users, catalysed by scientific collaborations on well-focused objectives.

As illustrated by Figure 1, the infrastructure strategy is that the EEFE comprises a network of Laboratories (each specialising in one aspect of economics/finance) and networked by a common infrastructure, sharing a Big data facility (with capacity in the 5-10 petabytes range). This will include real-time and historic economic, financial and social data. While each Laboratory will undoubtedly have its own specialist data (e.g. terabytes) accessible to the other Partners through the common infrastructure, given the 'Big data' requirements it is assumed that the facility may need to be hosted on a major commercial cloud service. The goal is to develop the platform, so that it can be used remotely by computer scientists to develop algorithmic trading systems, by economists to perform realistic simulations on the trading/risk hypotheses, and by regulators and industry professionals to analyse risk.

Methodology

The objective of the software architecture is to provide common economics/financial platforms for collaborative experimentation of how complex economic and financial systems behave and how to integrate knowledge across disciplines for the EEFE project Partners. This will ensure a common sharing of services via excellent delocalized centres that will support the financial and economic community for the research described in the preceding sections. These developments will benefit from continuous interactions and feedbacks between the developers and the users, catalysed by scientific collaborations on well-focused objectives. In order to be concrete as regards the methodology, the EEFE Platform & Infrastructure will take the advantage of the embryonic version developed at the UCL centre platform and infrastructure. The Algorithmic Trading & Risk Analytics Development Environment (ATRADE) developed at UCL is a 'financial wind tunnel', originally developed for algorithmic trading but now used for risk: systematic, institutional and high-frequency (HFT) [89,90]. The ATRADE platform was initially developed to speed up the development of our algorithmic trading systems. The goal is now to develop the platform, so that it can be used remotely by computer scientists to develop algorithmic trading systems, by economists to perform realistic simulations on the trading/risk hypotheses, and by regulators and industry professionals to analyse risk.

Appendix B describes the trading floor architecture of ATRADE within which an algorithmic trading system operates.

Technology

Again the ATRADE platform can be used to give the reader a flavour of the possible technology of the EEFE platform and infrastructure. For the EEFE platform, the EEFE partners will do a comprehensive redesign of the technology requirements, especially as the platform will be an 'economics' facility.

Rapid Prototyping: The current 'finance' platform is a framework for developing, trading, testing and evaluating algorithms/traders and their potential risk. The majority of users come from academia and are relatively inexperienced in the field of trading, especially algorithmic trading. Therefore, the platform provides them with a framework for algorithm development. Rapid prototyping requires usage of a simple programming language and also simple interfaces that provide as much embedded functionality as possible without a need for a heavy, low-level programming.

Financial Data Sources and Analytics: Financial data – both historic and real-time – is the key to success in traditional and algorithmic trading. Correspondingly, lack of data is a major impediment to academics conducting meaningful trading and risk research. Therefore, the UCL group is accumulating a significant source of historical financial data and real-time data feeds that are available to users of the platform. This is just a starting point that will be expanded considerably within the EEFE, as explained above. ATRADE aggregates, stores and processes real-time financial data and delivers it to the users for analysis through a set of dedicated interfaces.

Simulation & Real Trading: The platform allows users and algorithms to trade virtually or with real money with the use of a dedicated API. To provide this capability, the platform has a set of interfaces that allow the issuing and maintenance of orders, extraction and processing of market data to generate trading signals, extraction and processing of order data and finally management of information related to P&L and users' account information.

R & Matlab: The platform also provides the capability of interfacing to standard statistical/mathematical computing environments, such as R and Matlab. These statistical and mathematical computing environments are necessary for modelling and implementation of trading strategies. The two environments integrate with platform allowing the users to utilize their functionalities to analyse data, generate trading signals, evaluate risk etc.

Black Box and Multiple Models: A particularly interesting functionality of the platform, under development by the UCL group and foreseen to play a key role within the EEFE, is to evaluate the risk of black box models, without a need of handing the source of the models to anyone. This is particularly important for confidentiality, to eliminate IPR issues and ensure safety of the algorithmic trading models from a potential third party threats. We are working to enable the platform to support automated evaluation of multiple models concurrently, and also on generation of statistical-performance reports for every evaluation process.

Secure Remote Access: The EEFE computational platform for economics and finance will support external users, especially economists, wishing to experiment with traditional and algorithmic trading remotely. Expanding on the current model, the EEFE platform will provide an API that allows remote access to major functionalities of the platform. This involves making sure that the developed models and strategies are able to securely communicate with the platform.

A comprehensive description of the Trading & Risk platform is given in Appendix B.

Challenges and metrics of success

We feel confident that the EEFE partners will be able to agree an initial specification for the EEFE platform and infrastructure. As the partners begin their experimentation on economics, finance and policy it is likely that we will need to modify the platform and infrastructure to support their requirements. As an illustration, the London School of Economics (LSE) and UCL are investigating High-frequency trading and Flash crashes. LSE are investigating endogenous risk (endogenous risk refers to the risk from shocks that are generated and amplified within the system) and UCL are modifying their computational environment to support experimentation. Although ATRADE supports both real and virtual trading, LSE wishes to 'modify a real order book', requiring UCL to modify the system to take a real order book and then operate virtually on it.

The majority of the challenges faced by the EEFE Platform & Infrastructure relate to Big data, and especially ownership and access to financial data:

- Tracking the ownership of data that has been purchased or donated to the EEFE.
- Differentiating between FuturICT project data managed by the EEFE platform, data stored locally by a partner observatory, and data private to an industry partner.
- For each user defining what level of access they have to the data held by the EEFE.
- How the EEFE might provide some level of free access to academics participating in FuturICT while charging for access by industry partners.
- Managing IP created by the EEFE partners, such as value added analytics.

5 Concluding remarks and links with other exploratories

The European Economic and Financial Exploratory (EEFE) will allow the European community (and beyond) for the first time to explore different possible evolution scenarios for coupled economies and financial markets in a realistic way using a data driven approach. These scenarios may be used to evaluate the fluctuating growth paths of European economies, their (in)stabilities and the approach of crises. We are motivated by how this aim requires a novel interaction between current empirical and modeling approaches by using tools from various disciplines: computer science, statistical physics, econometrics, finance, complex system analysis and system engineering.

New measurement tools are also needed especially focused on map annotation and dynamics, as well as new models endowed with predictive power and realism. For this purpose, we plan to realize risk maps based on risk propagation models and we plan to simulate scenario of the economic situations based on the agent-based models developed in the project.

The EEFE will not develop in isolation but will be one of the core elements of FuturICT together with the exploratories of Technology, of Environment and of Society. The goal is to develop a fully global integration on a time scale of 10 years, with deliverables already working after 2 years. This is possible as some of our concepts are already starting at the national levels, such as the research priority area Behavioral Economics (BE-UvA) at the University of Amsterdam (UvA), the UNIGE Centre for Interdisciplinary Research on Economics and Financial Engineering in Genoa, the project Forecasting Financial Crises (FOC) funded within FP7 of the EU within the FET OPEN Scheme, the Financial Crisis Observatory at ETH Zurich and the Algorithmic Trading and Risk Platform at University College London. Moreover, close connection and cooperation is foreseen with several research centers and universities involved in FuturICT so as to address grand challenges in economic and finance (see [91]), to manage risk for more resilient societies (see [92]) and to share technologies, methodologies and tools (see [93]).

Webs of interactions between the observatories, services, infrastructures and facilities will develop in a natural way, since the systems that we study are intrinsically integrated. For instance, social instabilities may result from and/or cause economic strains. Therefore, we cannot disconnect the observatory for financial crises from the observatory of social instabilities. The same holds true for the entanglement between global health issues that include epidemics, which are fundamentally linked with the economics of health, of social welfare and of retirement pensions. Technology is driving modern societies, forcing them to change by providing new tools that can be exploited in previously unforeseen ways. As an example, the development of technology is at the basis of high frequency trading, which now accounts for more than 70% of trading volume on some western financial centres. This leads to completely new possibilities for better allocation of capital and access to financial liquidity for firms in the real economy. But this comes also with concerns of systemic risks and novel instabilities induced by the novel strategies implemented by the ecology of opportunistic investment and trading firms [94], as illustrated by the flash crash of May 6, 2010. Again, this requires strong collaboration and a common shared approach between the exploratories of technology and of economics and finance. Many other examples can be cited, Concretely, the integration between the observatories, and later the exploratories, will be achieved by the development of common data standards and by shared visions and methods of out-of-equilibrium complex integrative systems.

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Philip Treleaven is Professor of Computing at UCL, and Director of the UK Centre for Financial Computing a collaboration of UCL, London School of Economics and London Business School. The UK Centre has about 40 PhD students working on computational finance (algorithmic trading, risk) with Banks, Funds and Regulators. The Centre has an experimental environment and a large data facility of financial data, including real-time data. Currently the Centre focuses on algorithmic trading and risk (systemic, institutional, and high-frequency). The Centre is expanding its activities into economic and social modelling, referred to as computational social science.

Appendix A. Definitions and concepts

Computational Science

Computational science has revolutionised Physics (it has become its third pillar together with theory and experiments) as well as the Life Sciences, yielding for the later the new disciplines of bioinformatics and systems biology. This has led for instance to an understanding of the fundamental structure of human DNA sequences. Of comparable importance is the application of computation analytics to solving major problems in economics and finance that can have a catastrophic Global economic impact.

In terms of definitions of closely related and overlapping terms:

– Computational Science – Computational science is concerned with constructing mathematical models and quantitative analysis techniques and using computers to analyse and solve scientific problems. In practical use, it is the application of computer simulation and other forms of computation to problems in various scientific disciplines, such as the computational biology, computational neuroscience, computational chemistry, computational physics and computational fluid dynamics.
– Complexity Science – Complexity science is a broad term for understanding a range of complex phenomena. If you break down a 'complicated' system into its basic components and analyse how the components behave, you can recreate the behaviour of the whole system by running all the components together. There are a wide variety of 'complex' scientific and engineering problems, though, that defy this type of analysis. The behaviour of a complex system is an emergent property of the interactions of the components.

In broad terms, computational science involves using computation to study scientific problems through the collection and analysis of data, and/or the construction and testing of computer-based models of a system or phenomenon under investigation, complementing theory and experimentation in traditional scientific investigation. Computational science seeks to gain understanding of science principally through the use and analysis of mathematical models on high performance computers. Computer simulations provide both qualitative and quantitative insights into many phenomena that are too complex to deal with by traditional analytical methods or too expensive to study by experimentation.

Computational science has two distinct branches:

– **Data Mining** – knowledge discovery that extracts hidden patterns from huge quantities of data, using sophisticated differential equations, heuristics, statistical discriminators (e.g. hidden Markov models), and artificial intelligence machine learning techniques (e.g. neural networks, genetic algorithms, support vector machines).
– Computer Modelling – simulation-based analysis that tests hypotheses. Simulation is used to attempt to predict the dynamics of systems so that the validity of the underlying assumption can be tested.

A.1 Computational Economics

Computational economics is a research discipline in economics and computer science [95]. Areas encompassed under computational economics include agent-based computational modelling, computational econometrics and statistics [96], computational finance, computational modelling of dynamic macroeconomic systems and transaction costs, computational tools for the design of automated Internet markets, programming tools specifically designed for computational economics, and pedagogical tools for the teaching of computational economics. Some of these areas are unique to computational economics, while others extend traditional areas of economics by solving problems that are difficult to study without the use of computers.

Computational economics researchers use computational tools both for computational economic modelling and for the computational solution of analytically and statistically formulated economic problems.

For example, with regard to computational modelling tools, Agent-Based Computational Economics (ACE) is the computational study of economic processes modelled as dynamic systems of interacting agents. Here "agent" refers broadly to a bundle of data and behavioural methods representing an entity constituting part of a computationally constructed world. Agents can represent social, biological, and/or physical entities. Starting from initial conditions determined by the modeller, an ACE model develops forward through time driven solely by agent interactions.

With regard to computational solution tools, examples include software for carrying out various matrix operations (e.g. matrix inversion) and for solving systems of linear and nonlinear equations. For a repository of public-domain computational solution tools, visit here.

A.2 Computational Finance

Computational finance or financial engineering is a cross-disciplinary field, which relies on computational intelligence, mathematical finance, numerical methods and computer simulations to make trading, hedging and investment decisions, as well as facilitating the risk management of those decisions [97]. Utilising various methods, practitioners of computational finance aim to precisely determine the financial risk that certain financial instruments create.

There is no exact definition of computational finance, and significant overlap exists with related areas, such as financial modelling, financial mathematics and financial engineering. As an attempt to delineate these areas:

- Financial Modelling – the most general of the related terms, covers computation of finance problems, such as option pricing, with the central aim of modelling valuation under uncertainty.
- Mathematical Finance – is the branch of applied mathematics concerned with the financial markets.
- Financial Engineering – focuses on financial innovation, which aims to produce new securities, specifically derivative for the options and futures markets.
- Computational Finance – is a cross-disciplinary field that focuses on the financial services industry and relies on mathematical finance, numerical methods and computer simulations to make trading, hedging and investment decisions, as well as facilitating the risk management of those decisions.

A.3 Computational Geometry

Computational Geometry is concerned with the design, analysis, and implementation of algorithms for solving geometric problems. Examples include: range searching (preprocess a set of points, in order to efficiently identify points that are located inside a query region), nearest neighbour (pre-process a set of points, in order to efficiently find which point is closest to a query point) and ray tracing (given a set of objects in space, produce a data structure that efficiently tells which object a query ray intersects first).

Whereas computational statistics and machine learning are used extensively in economics and finance, a comprehensive list of techniques spans: symbolic and algebraic computing, numerical analysis, computational geometry, visualization and graphics, plus artificial intelligence and computational statistics. Short descriptions are presented, and Table 1 attempts to summarize the influential AI (artificial intelligence) and computational statistics techniques.

A.4 Computational Statistics

Computational statistics is concerned with statistical methodologies where intensive computing is an integral component usually at the interplay between computer science and data analysis. It is built on the mathematical theory and methods of statistics, and includes visualization, statistical computing, and Monte Carlo methods. The emphasis in computational statistics is often on exploratory methods. These include methods for statistical inference such as re-sampling methods (e.g. bootstrap and jack-knife), and Markov chain Monte Carlo methods as well as methods for regression and classification. For example, the evaluation of posteriors in Bayesian analysis for complex statistical models is essentially only possible by using the iterative simulation technique of Markov chain Monte Carlo methods. In frequentist statistical inference, the computational statistical method of bootstrapping is an indispensable tool when asymptotic results are not available.

It is difficult to find a suitable taxomony for computational statistics. One possibility is to subdivide techniques into:

- **Probability Density Estimation** – covers the methods of constructing an estimate of an unobservable underlying probability density function from observed data. Examples are kernel density estimation, nearest-neighbour estimation and maximum penalized likelihood estimation.
- **Statistical Inference** – makes inferences concerning some unknown aspect of a population from a random sample. This includes the methods of point estimation and interval estimation. These methods can be performed using both traditional frequentist methods, such as maximum likelihood method and minimum mean squared error, or Bayesian methods such as Markov chain Monte Carlo methods and Kalman filter.
- **Regression** – models and analyses a relation between a dependent variable and one or more independent variables. This has a strong connection to Supervised learning from Artificial Intelligence. However, the main focus in statistics is to determine the relation between the dependent variable and the independent variables not to obtain the most accurately prediction of the dependent variable as in supervised learning. The example of models in this category is generalized linear model and generalized additive model.

A.5 Artificial Intelligence

The term Artificial Intelligence (AI) has a range of definitions and subdivides into: a) symbolic reasoning (e.g. logic, rule-based and expert systems) and b) subsymbolic/machine learning (e.g. neural networks and evolutionary computation).

Symbolic (or knowledge-base) AI is concerned with attempting to explicitly represent human knowledge in a declarative form employing facts and rules. The classic model is a rule-based 'expert' system, comprising a domain specific knowledge base (the facts), a set of production rules (the rules), and an inference engine that processes the knowledge encoded in the knowledge base to respond to a user's request for advice.

Sub-symbolic (or machine learning) AI refers to a system capable of the autonomous acquisition and integration of knowledge. This capacity to learn from experience, analytical observation, and other means, results in a system that can continuously self-improve and thereby offer increased efficiency and effectiveness. Sub-symbolic systems further subdivide into:

– **Supervised Learning** – covers techniques used to learn the relationship between independent attributes and a designated dependent attribute (the label). Most induction algorithms fall into the supervised learning category. Examples are: Regression Trees, Discriminant Function Analysis.
– **Unsupervised Learning** – covers learning techniques that group instances without a pre- specified dependent attribute. Clustering algorithms are usually unsupervised. Examples are: Neural Networks, Self-Organizing Maps (SOM), Principal Components Analysis.
– **Reinforcement Learning** – is a sub-area of machine learning concerned with how an agent should take actions in an environment so as to maximize some notion of long-term reward. Reinforcement learning algorithms attempt to find a policy that maps states of the world to the actions the agent ought to take in those states.

A.6 Risks

– **Trading risk** – the failure to correctly model the risk of the financial instruments being traded.
  – *Portfolio risk* – failure to model the 'risk' associated with individual instruments and a target portfolio of financial instruments.
  – *Regime change risk* – failure to model a fundamental change in the behaviour of the markets, including exogenous risks such as terrorist attacks.
  – *Equity risk, correlation risk, interest rate risk, currency risk, commodity risk, market liquidity risk.*
– **Economic risk** – the risk of collapse of an institution, market or entire financial system.
  – *Institutional risk* – the risk associated with trading including algorithms and their impact on a financial institution.
  – *Credit risk* – credit risk from lending, counterparty credit risk, settlement risk.
  – Liquidity risk – risk from not being able to sell an asset due to lack of counterparties; also includes the opportunity risk not to be able to buy desirable assets for lack of cash.
  – *Systemic risk* – is the risk of freezing or even collapse of an entire market or an entire financial system.
– **Operational risk** – the risk of execution failure of the normal functions of an organization due machine, system and/or humans as well as external physical or environmental risks.
  – *Law and compliance, government affair* – enforceability risk, regularity risk, legislation risk.
  – *Operations, controllers, IT, Tax department, facilities, human resources* – transaction risk, system risk, operation control risk, taxation risk, disaster risk, people risk.

A.7 Stability

Economic stability refers to an absence of excessive fluctuations in the macro-economy. An economy with fairly constant output growth and low and stable inflation together with low volatility stock market prices would be considered economically stable. An economy with frequent large recessions, a pronounced business cycle, very high or variable inflation, or frequent financial bubbles and crises would be considered economically unstable.

Appendix B. Trading Floor Architecture of the Algorithmic Trading & Risk Analytics Development Environment (ATRADE)

To understand ATRADE, which has been developed by the UCL group, it is useful to introduce the trading floor architecture within which an algorithmic trading system operates.

Trading platforms can be considered three-tier systems, where the first tier consists of external communication elements, the second tier is responsible for internal communication, and finally the third layer provides the actual business logic. Cisco's Trading Floor presents a good representation of a typical architecture of a trading system.

The bottom layer of the Trading Floor architecture represents the wider, external communication layer and the low level hardware and network architecture of the platform, as well as the external systems with which it exchanges information. The Trading Floor architecture also defines the external communication layer from the data-streams perspective, and it specifies the 'market data' stream and 'trading orders' stream.

The top layer of the Trading Floor architecture describes the logic behind all the modules of the platform. Typically, this includes: the connectivity engines, data aggregation units, data processing elements, order routing, execution elements, trading strategy elements, graphical and programmatic interfaces, monitoring tools and many more, depending on the requirements and specification.

The middle layer of the Cisco's Trading Floor architecture is the service layer that allows internal communication within the platform. The internal communication system is a backbone of every platform. It needs to be reliable and fast; it also needs to be flexible and modular. The internal communication is necessary as a result of the distribution of elements of the platform.

ATRADE Core Modules

The core modules of the system are listed below.

FIX Engine module: A common format for the order and market data transport is the FIX protocol. The applications that handle FIX messages are called FIX Engines. They are designed to send/receive high volumes of FIX messages, translate the messages to relevant internal formats of the architecture, and interface to all the relevant modules of the platform.

Feed Handlers: When the market data is handled by the FIX Engine and passed to the rest of the elements of the system, it needs to be cleansed, processed and aggregated. The Feed Handler module provides functionalities to clean the data from outliers, gaps and other statistically significant problems to make sure that the data is of high quality.

Price Engine: The goal of the engine is to allow an automatic pricing of securities, using inputs from different sources and adopting financially consistent pricing models. The Price Engine needs to be designed to support concurrent, real-time calculations for hundreds of assets at the same time.

Risk Modelling: The risk engine is a management system designed to identify the risks associated with a given set of assets. The engine provides a set of comprehensive measurement tools to assess, control and communicate risk.

Order Management: The Engine is used for rapid order entry and processing, it facilitates and manages the order execution, typically through the FIX Engine. The Order Management systems often aggregate the orders from different channels to provide a uniform view. The engine allows input of single and multi-asset orders to route to the pre-established destinations.

Algorithmic Trading: This module supports the use of trading strategies that issue and manage orders with use of an embedded logic coded within the algorithm of the strategy. This allows the logic of the algorithm to decide on aspects of the order such as the optimal timing, price or quantity of the order.

Trading Systems and Alerting modules: These modules provide a means of manual trading by allowing the users visual or audio access to the platform. The two module types describe (in a visual or audio way) the states of the markets and selected assets, and also provide a graphical representation of analytical data (in case of the Trading Systems).

Execution Monitors, Performance Dashboards and Compliance Surveillance: These modules allow monitoring of the architecture's performance. The modules also monitor the compliance of the performance and behaviour with predefined policies.

ATRADE Platform

The ATRADE platform (Fig. 2) consists of a set of distributed, multi-threaded, event-driven, real-time, Linux services communicating with each other via an asynchronous messaging system. The platform allows multi-user virtual and real trading. It provides a proprietary API to support development of algorithmic trading models and strategies. It allows an advanced trading-signal generation and analysis in real-time, with use of statistical and technical analysis as well as the data mining methods. It provides data aggregation functionalities to process and store market data feeds. Finally, the platform allows back and forward testing of trading strategies.

The following modules of the platform summarize the undertaken work to date:

Back-End Services: This module provides the core of the platform functionalities. It is a set of services that allows connection to a set of brokers and data providers, propagation processing and aggregation of market data feeds, execution and maintenance of orders, and management of trading strategies in a multi-user environment.

Front-End GUI Client: This is a graphic user interface that allows visual management of trading strategies. It allows the user to visualize market data in the form of charts, provides a market watch grid with a capability of manual trading and modification of positions generated by trading models, provides a dynamic

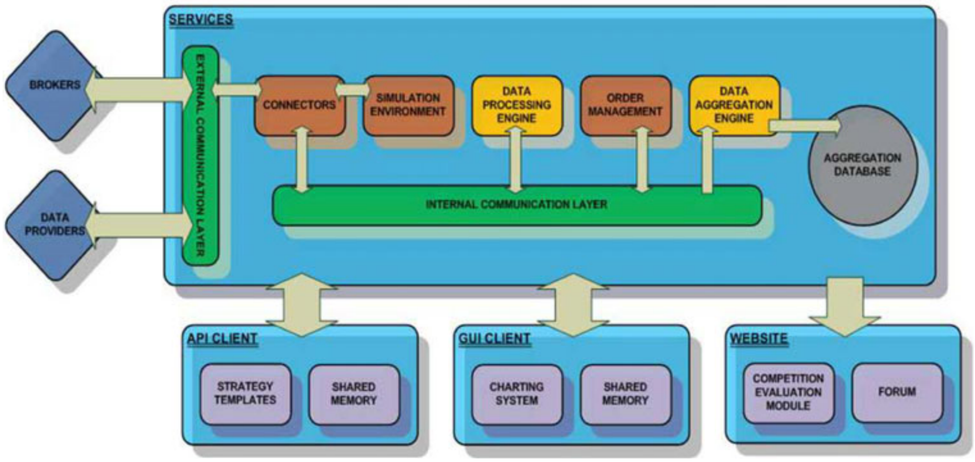

Fig. 2. UCL ATRADE Platform and Modules.

visualization of an order book, and allows users to observe information on events relevant to the users environment.

Front-End Competition Evaluation Module: This module supports trading competitions and allows organizations to monitor/display the trading results of users utilizing the platform. The framework is a web-based graphic user interface. Its functionalities allow the generation of a ranking of users (on the basis of statistics of performance of their trading models) that allows classification of users.

Front-End API Client: This provides a set of interfaces that can be used via a users' favourite IDE (Integrated Development Environment) to implement and test trading models. The API provides strategy templates to simplify access to some of the interfaces and defines generic structure of the strategies.

The business logic of the platform is similar to the one utilized in the Cisco's Trading Floor. The following elements are the main platform modules:

Connectors: This functionality provides a means of communication with the outside world; with the brokers and the data providers. Each of the outside venues utilized by the platform has a dedicated connector object responsible for control of communication.

Internal Communication Layer: The idea behind the use of the internal messaging system in the platform draws from the concept of event-driven programming. The trading platform utilizes events as a main means of communication between the elements within the platform. The elements, in turn, are either producers or consumers of the events.

Aggregation Database: This provides a fast and robust DBMS functionality and enables the platform to store, extract and manipulate large amounts of market data. The storage capabilities of the Aggregation element not only allows a back-testing of the strategies with use of historical data but also enables other, more sophisticated tasks related to functioning of the platform including data analytics on the basis of market data, data analytics on the basis of trades, variety of risk analysis, evaluation of performance of trading models and many more.

Order Management Engine: This provides four main functionalities to the platform. Firstly, it allows execution/maintenance of orders triggered by trading strategies. Secondly, the orders are synchronized with the selected brokers.

API Client: This is an API (Application Programming Interface) that enables development, implementation and testing of new trading strategies with use of the developers favourite IDE (Integrated Development Environment). The API allows connection from the IDE to the server-side of the platform to provide all the functionalities the user may need to develop and trade.

Shared Memory: This provides a buffer-type functionality that speeds up the delivery of historical data to strategies and the analytics-related elements of the platform (i.e. the technical analysis library of methods), and, at the same time, reduces the memory usage requirement.

Strategy Templates: The platform supports two generic types of strategies; push and pull. The push type registers itself to listen to a specified set of financial assets during initialization, and the execution of the strategy is triggered each time a new data feed arrives to the platform. This type is dedicated to very quick, low-latency, high-frequency strategies and the speed is achieved at the cost of small shared memory buffers.

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