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THE INTERNATIONAL MONETARY SYSTEM AND INTERNATIONAL FINANCIAL SYSTEM AS AN ANALOGY TO THE COPERNICAN HELIOCENTRIC SYSTEM: A SIMPLE MULTI-LAYERS NETWORK MODEL WITH SIMULTANEOUS REGIME CHANGES

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ABSTRACT

The evolution of the IMS and IFS in the past several hundred years can be viewed through the lens of the Copernican heliocentric system developed over 500 years ago. We trace out the evolution across regimes of the IMS and IFS in terms of network representations of the Copernican system. We provide a simple, fully testable theoretical model whose assumptions are based on these representations. The IMS and IFS are described by a two-layer graph whose three key features (hub, core, distances) are affected by nonlinear joint regime changes linked to a technological, institutional, geopolitical and regulatory environment variable. We conclude with a discussion of some perspectives of the future of the international monetary and financial systems. Our analysis is based on economic history, theory and some resonant concepts from astrophysics.

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1 Introduction

In this paper we argue that the evolution of the International Monetary System (IMS) and International Financial System (IFS) in the past several hundred years can be viewed through the lens of the Copernican heliocentric system developed over 500 years ago. Our contribution is twofold. On the one hand, we connect literatures in economic history and the theory of complex networks with some resonant concepts from astrophysics. Elaborating on the equivalence of single-hub tree networks diagrams and stellar systems, we trace out the evolution across regimes of the IMS/IFS in terms of network representations of the Copernican system. The specific network representations provided by the analogy allows us to propose a novel reading of monetary and financial history, shedding light on both long-term trends and future prospects. We also provide a simple, fully testable theoretical model whose assumptions are based on these representations. The IMS and IFS are described by a two-layer graph whose three key features (hub, core, distances) are affected by non-linear joint regime changes linked to a technological, institutional, geopolitical and regulatory environment variable. We conclude with a discussion of some perspectives for the future of the international monetary and financial systems.

There are five main foundations of the analogy. The first foundation, which is also the starting point of our reasoning, is that the Copernican system revolutionized the representation of the universe from a theoretical model that preceded observation. This point is not necessarily the best known : Copernicus is systematically associated with the discovery of the heliocentric system, but the essentially theoretical nature of his contribution is more rarely mentioned. Yet it helps explain why, unlike Galileo, the Church did not pursue Copernicus, as his work was widely regarded as a mathematical treatise. In fact, Copernicus' sine tables, essential to the study of any stellar system, whatever its center, remained the standard for centuries. As the science historian Owen Gingerich states, "in the first chapters, Copernicus gives his strongest arguments in favor of a model of the planetary system with the sun at its center - arguments based on simplicity, harmony and aesthetics, since it was impossible at that time, before the invention of the telescope, to find observational evidence of the Earth's motion." (Gingerich, 2004, p. 54). The same question of the tensions between theoretical modeling and observation arises in the case of the IMS/IFS. Their forms evolve, and the ability to develop relevant theoretical models and at the same time define the appropriate measurements to provide an empirical validation is a true challenge, as illustrated for example by the rise of cryptocurrencies and digital currencies in general.

The second main foundation of the analogy is that the Copernican model was not only innovative, but also much simpler than the previous models, as illustrated by Figure 1 below. This aspect of Copernicus' work is not necessarily well known either. The Ptolemaic system (Figure 1 left), which preceded the Copernician system (Figure 1 right) as the reference representation of the movement of the Sun and planets, had undergone successive additions over time as observations became more precise, in order to remain compatible with these observations. In this context, "his successors admired Copernicus for a completely different aesthetic reason [than the heliocentric theory], namely the elimination of [epicycles]. (Gingerich, 2004, p. 63-64). In the augmented Ptolemaic system, the planets revolve around the

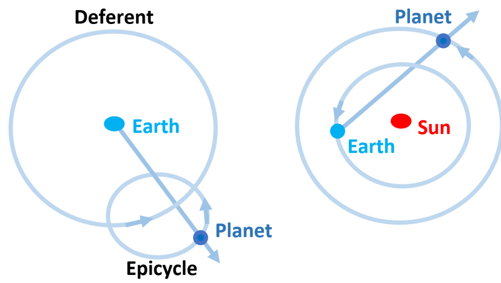

Figure 1 – Augmented geocentric system of Ptolemy (left), heliocentric system of Copernicus (right)

Earth - not directly on orbits, but on a small circle (epicycle) which itself rotates on a large circle (deferent). In comparison, the Copernican model is not only radically innovative, but also much simpler. Our analogy is inspired by this search for simplicity in modeling.

The third main foundation of the analogy is that the Copernican system paved the way for further developments in astrophysics, from the 16th century to the present : "Until a massive and precise observation protocol was developed by Tycho Brahe [in the last years of the 16th century], the necessary data was not available. Once available, it took less than fifteen years for Kepler to identify the elliptical compression of the orbits" (Gingerich, 2004, p. 181). This includes the discovery of the elliptical orbits by Kepler in the early 17th century, the existence of planetary satellites, the multiplicity of solar systems, etc. Our analogy between the international monetary and financial systems and stellar systems is essentially inspired by Copernicus' heliocentric model, but also by these later developments. A recent development, in particular, constitutes the fourth foundation of the analogy : modern astrophysics documents the life cycles of stars and their stellar systems. In other words, if the characteristics of the IMS and IFS are not time-invariant, neither are those of stellar systems, considering a relevant time horizon, which is that of astrophysics. This life cycle, marked by a succession of periods in which the stars and their solar systems display essentially homogeneous characteristics, is illustrated by Figure 2 :

"We identify four galaxy groups [...] that can be evolutionarily linked through a life cycle [...]. Galaxies first consume their gas mostly through [...] star formation (C1) ; then enter into a transition phase of intermediate gas richness (C2-C3) [...] ; before settling into retirement as [...] systems with residual levels of [...] activity (C4)." (Yesuf and Ho, 2020). The monetary and financial systems are also characterized by successive relatively homogeneous periods. For the last century and a half, for the international monetary system, we distinguish between the Classical gold standard, the Gold exchange standard, Bretton Woods and the Managed float ; and for the international financial system we distinguish between the pre-World War first era of globalization, disintegration during the interwar and Bretton Woods period and rejuvenation as the second era of globalization since.

The fifth and last main foundation of the analogy is that the network representations

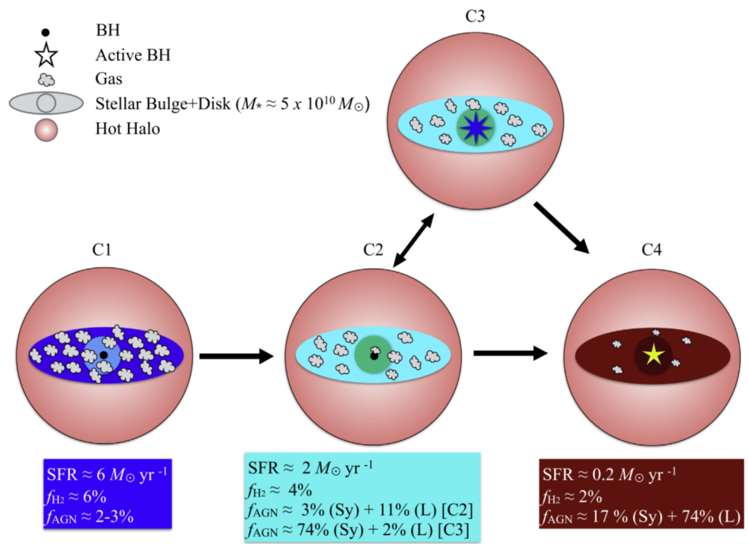

FIGURE 2 – Schematic diagram of clusters of stars C1 to C4 over lifecycles (source : Yesuf and Ho, 2020

used today for the study of the IMS/IFS can be directly transposed into the language of stellar systems, as illustrated by the examples of Figure 3(left) which represent networks of currency quotes, and Figure (right) representing networks of stock markets prices.

Stellar systems are composed of stars, planets orbiting the stars, and satellites orbiting the planets. Distances are measured by the radii of the orbits. Monetary and financial networks are composed of hubs, secondary hubs, and weakly connected nodes. Distances are measured by the lengths of the edges. These three common characteristics of stellar systems, on the one hand, and monetary and financial systems, on the other hand, directly support the analogy-inspired modeling that we propose in what follows.

Based on these five foundations of the analogy, the rest of the paper is organized as follows. Section 2 presents the methods of the network modeling. Section 3 details the historical evolution of the IMS/IFS and provides a summary of the main concerns relating to current developments in IMS/IFS from the perspective of this original network modeling. Section **??** proposes a testable theoretical model that synthesizes the whole range of literatures on which the analogy relies, and Section 5 concludes by formulating some main lessons and discussing limitations of the modeling strategy.

2 The Methods of the analogy

2.1 Modeling monetary and financial systems as stellar systems

In what follows, we detail the analogy to the Copernican heliocentric system as support for our description of the history of the IMS and IFS in section 3, and the theoretical modeling in section 4. We do this in three steps : the equivalence of tree network diagrams and

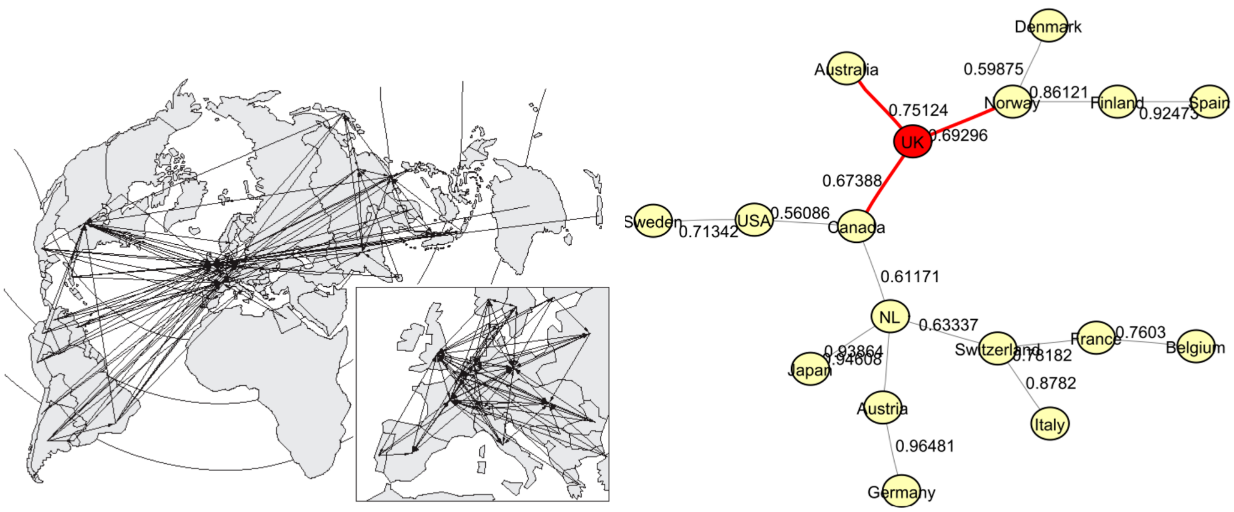

FIGURE 3 – Network of currencies quotes, 1900 (left, source : Flandreau and Jobst, 2005), Network of stock markets prices, Interwar (right, source : Bastidon et al. (2023))

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star system diagrams ; the parallel between star life cycles and tree network regime shifts ; and the causal variables of regime shifts.

At a general level, on the one hand, over the past century and a half, the structure of monetary and financial systems has been essentially stable within major eras, but very different from one era to another. This first specific feature leads us to use a regime-switching network model in which key network characteristics are stable within eras but can vary from era to era. It is discussed in detail in subsection 2.2. On the other hand, in terms of networks, a stellar system corresponds to a specific network model, i.e. a tree network. This second feature is discussed in detail in the current subsection. The three stages of Figure 4 describes the equivalence between a tree network diagram characterized by the three key characteristics of hub(s), core (nodes located in the close neighborhood of the main hub), and distances between the nodes (Figure 4 left) and a Copernicus-type stellar system diagram (Figure 4 right).

As documented in the existing literatures in Financial macroeconomics and Statistical mechanics, tree networks also describe in a relevant way monetary and financial systems (see notably, for minimal spanning trees, Bastidon and Parent, 2022 ; or Bastidon et al., 2020). This observation of the relevance, documented in their respective reference literatures, of the same network model for the representation of stellar systems and monetary and financial systems leads us to take, as a starting point for the modeling of monetary and financial systems, tree network models whose structures are equivalent to those of star systems (Figure 4). In what follows, we systematically provide both diagrams : the network diagram for comparability with the existing literature, and the star system diagram for readability and as a support for the discussion based on the analogy.

In the IMS representation, the three key features of the stellar system / network (Figure

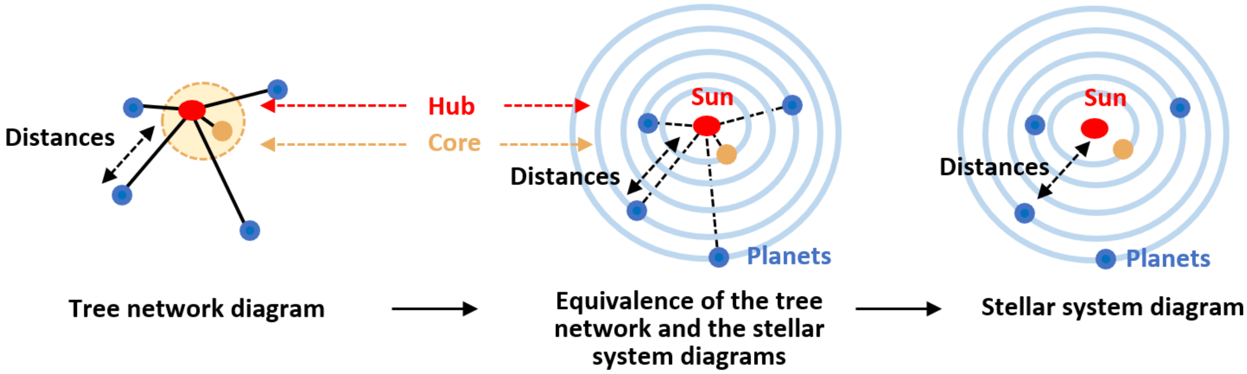

FIGURE 4 – From tree network diagrams (left) to stellar system diagrams (right). Schematic representation of the equivalence (middle) of the structure of a weighted tree network with one hub, and a stellar system.

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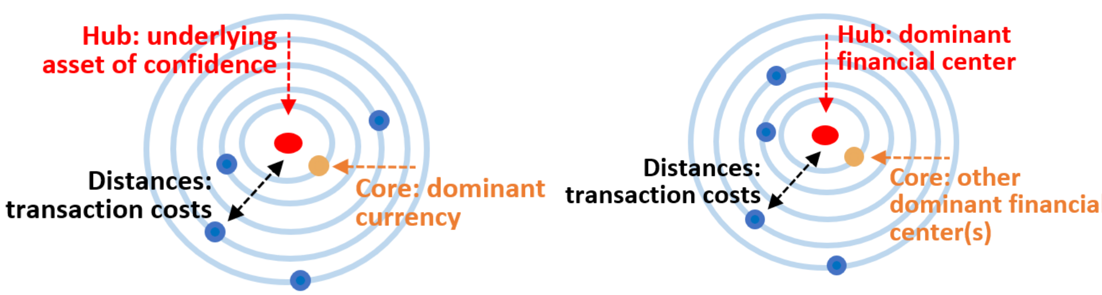

FIGURE 5 – Key features of the stellar system diagram of the IMS (left) and IFS (right).

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5 left) are then the hub, corresponding to the main underlying asset of confidence (nominal anchor), whether tangible (gold) or intangible (monetary policy credibility, Willems and Zettelmeyer, 2022) ; the core, corresponding to the dominant currency(ies), and distances corresponding to transaction costs in foreign exchange operations, low for permanently fixed exchange rates and high otherwise. For the IFS representations, the three key features (Figure 5 right) are the hub, corresponding to the dominant financial center ; the core, corresponding to other dominant financial center(s) ; and distances, corresponding to transaction costs in international capital flows, low for low regulation and high for high regulation.

2.2 The IMS and IFS as a 2-layer multivariate regime switching graph model

To model the joint long-term dynamics of the monetary and financial systems, the network representation of the IMS and the IFS are included in a simple 2-layer regime-switching network model summarized by Figure 6. The first layer corresponds to the IMS (Figure 6 left) and the second layer to the IFS (Figure 6 right), both described by the previously presented three key variables of networks structures i.e. their hub (upper panels), core (middle panels) and distances (bottom panels). For each layer, each variable has two or three possible states, i.e. for the hub of the IMS, gold standard / no gold standard (upper right) ; or for the hub of the IFS, London / New-York (upper left), over four eras : the Classical gold standard in the 1st era of globalization, the Gold exchange standard in the Interwar, the Bretton Woods era, and the managed float in the 2nd era of globalization.

Figure 7 provides, for the IMS and IFS layers (in columns) and for each eras (in rows), the two equivalent tree network and stellar system diagrams. These representations are discussed in detail by era in Section 3 and form the basis of the theoretical model developed in section . As a preliminary, in the following we introduce the causal variables of the system regime switchings.

2.3 Why do the IMS/IFS regimes switch ?

The stages of the life cycle of stars are well documented. The transition from one type of star to another depends on the nature of the reactions that take place (e.g., Yesuf and Ho, 2020). By contrast, the causes of the emergence of specific network structures, corresponding to IMS/IFS regime switchings, are less widely studied, to the point where they would even remain "terra incognita" in the literature (Flandreau and Jobst, 2005). Based on different types of literature, we identify four factors which may explain regime switches. These are : changes in technology, changes in institutions ; geopolitical forces (including major conflicts) and changes in governance (e.g., regulation). In the theoretical model proposed in section **??**, we refer to these causes as "components" of the environment variable, which is composed of four distinct time-series vectors.

In detail, the technological component refers to the global advances and convergence in technology and growth dynamics. For example, Sylla (2002) highlights the crucial nature of

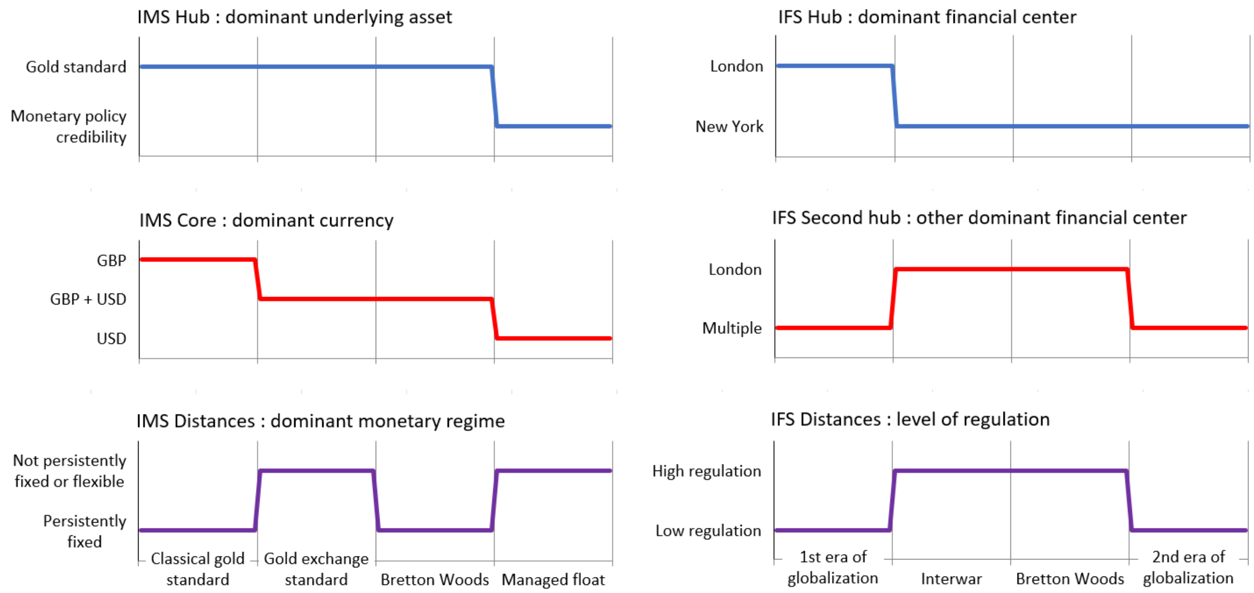

FIGURE 6 – Switching regime network model, IMS layer (left) and IFS layer (right) : overall dynamic representation.

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the prior financial revolutions in the three economies that were pioneering in creating durable monetary and financial institutions (the Netherlands, the UK, then the USA) . He argues that financial revolutions and, more generally, the dynamics of financial development came before the industrial revolutions (especially in the cases of the UK and US) that gave these countries economic and financial dominance in the past four centuries.

The institutional component refers to major institutional changes in the organization of monetary and financial systems. An example with particularly noteworthy consequences was the foundation in 1913 of the modern Federal Reserve System, which led to the consolidation of U.S. banking and financial institutions and markets This dramatic institutional innovation allowed the US monetary and financial system to catch up to its clear dominance in global economic performance achieved by 1900. This set the stage for the later dominance of the U.S. dollar.

The geopolitical component refers first to major conflicts and the associated demographic and economic costs, especially World Wars I and II. (see, in particular, Kindleberger, 1973 on the "formation of financial centers"). It also refers to other geopolitical factors e. g., alliances and the end of colonial empires. From this perspective in particular, Cassis (2010) ; or Eichengreen et al. (2018) point out that the persistence of, respectively, international financial centers and international monetary systems, associated with the liquidity of local financial markets, the availability of trade finance, and the interest rates on newly-issued debt, would be overestimated.

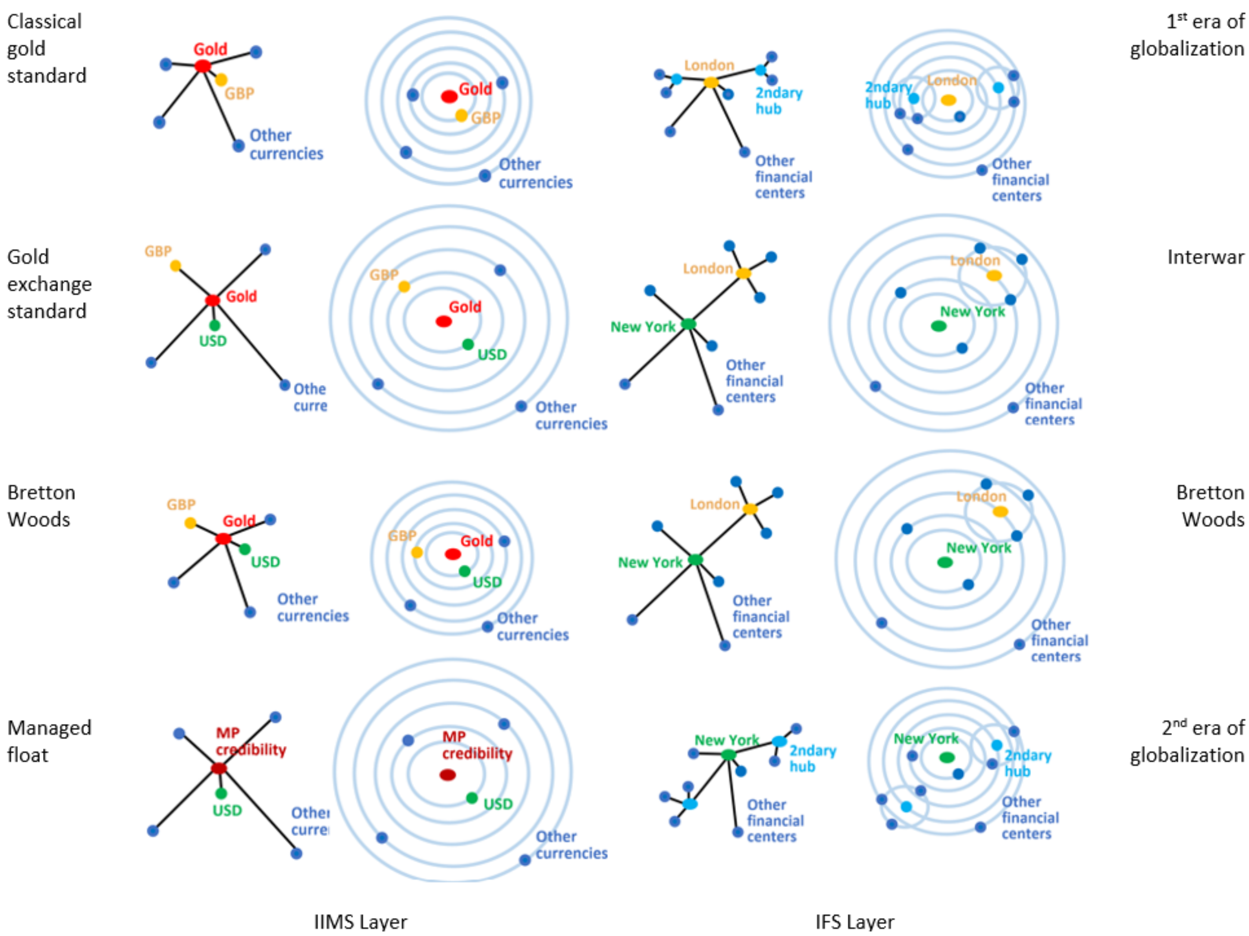

FIGURE 7 – Switching regime network model, IMS layer and IFS layer : network and stellar systems diagrams.

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Finally, the governance component refers both to the role of international organizations like the councils of foreign bond holders before WWI, and subsequently the IMF, G10, G20, and the BIS in enforcing and amending the operating rules of the game of the IMS and IFS. It also refers to major reform proposals and their implementation. This was notable in the era of the Classical Gold standard in proposals by e.g. Ricardo, Jevons, Marshall, Fisher, Wicksell and Keynes (Bordo, 1984), some of which were partially implemented after World War I at the Genoa conference (1922). During the era of the Gold exchange standard, a key proposal for reform by Ragnar Nurske (Nurkse, 1944) and then by Keynes (1941) and White (1943), the adjustable peg, was later adopted in the Bretton Woods Agreement of 1944. The alternative case for floating exchange rates made by Gottfried Haberler was rejected (Bordo et al., 2002). In the case of the Bretton Woods regime, proposals for reform to create a global central bank by Triffin (1960) and others were not adopted but the case for floating by Milton Friedman (Friedman et al., 1953) was ultimately implemented with the collapse of the Bretton Woods system in 1973.

These components of the environment variable form both the threshold variables and the explanatory variables for the joint changes in the three characteristics of the IMS layer and the IFS layer of networks in our proposed model.

3 Historical evolution of the IMS and IFS

3.1 Classical Gold standard

In this section, we propose an original reading of the historical evolution of the IMS and IFS, relying on the analogy. For each era, this reading is based on the equivalents tree network and stellar system diagrams, summarized in Figure 8.

Figure 8 presents the Classical Gold standard. The model at a glance highlights the central place of Sterling as the IMS core, based on Gold as the IMS hub, and the financial center in London as the IFS hub. It also emphasizes low transaction costs in both foreign currency transactions and international capital flows (IMS and IFS short distances), i.e the absence of capital controls and major advances in communications after the laying of the first transatlantic cable (Kavesh et al., 1978).

In detail, the representation of the IMS layer provides a relevant description of the role of Gold (IMS hub) as money, with special properties as store of value, means of exchange, and unit of account. In this context the pound sterling (IMS core) convertible into gold evolved as the key currency because of network externalities for trade such as invoicing, the standard of value property being based on safe assets, political stability etc. The representation of the IFS layer encompasses the development in the nineteenth century of London as the IFS hub, as the principal securities and commodities markets, as well with the other European financial centers in the IFS core. The networks that developed were based on path dependency. This followed a path dependent process based on Sterling bills as the key financial instru-

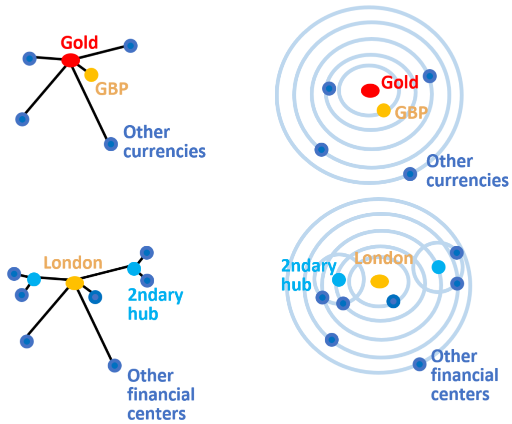

FIGURE 8 – Tree network (left) and stellar system diagrams (right), Classical Gold standard. International monetary system (upper), International financial system (lower).

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ment (Coppola et al., 2023). Note that the correspondence between dominant currency and dominant financial center, observed for each of the eras described in this section, constitutes one of the stylized facts underpinning the theoretical modeling assumptions in Section 4.

3.2 Gold exchange standard

Figure 9 presents the model for the gold exchange standard era. It mainly highlights the decline in the central place of Sterling, in the IMS core, as the dominant international currency in favor of the dollar beginning in the 1920s. In the IFS, the financial center in London, as the hub of the IFS, gradually has been replaced by New York. The era is characterized by both high transaction costs in foreign currency transactions and international capital flows, seen in long distances in both the IMS and IFS, reflecting the closing of financial markets during World War I and the advent of exchange and capital controls.

The main stylized facts of the period, captured by the model, are as follows. In the IMS layer, Gold remained the hub, but the core is now composed of Sterling and Dollars. The position of both depends on their track record in maintaining convertibility into gold (Eichengreen and Flandreau, 2009). Sterling devolves with the U.K.'s loss of economic power. This corresponds to the geopolitical component of the transition environment variable. The IFS layer displays weak networks (long distances) centered on New York as the IFS hub ; and London as the IFS core, as New York takes over in the sovereign debt and money markets. This corresponds to the technological and institutional components of the explanatory and transition environment variable.

3.3 Bretton Woods

Figure 10 presents the Bretton Woods era. The model mainly emphasizes the central place of the US dollar in the IMS core, based on gold as the IMS hub, and the rise to do-

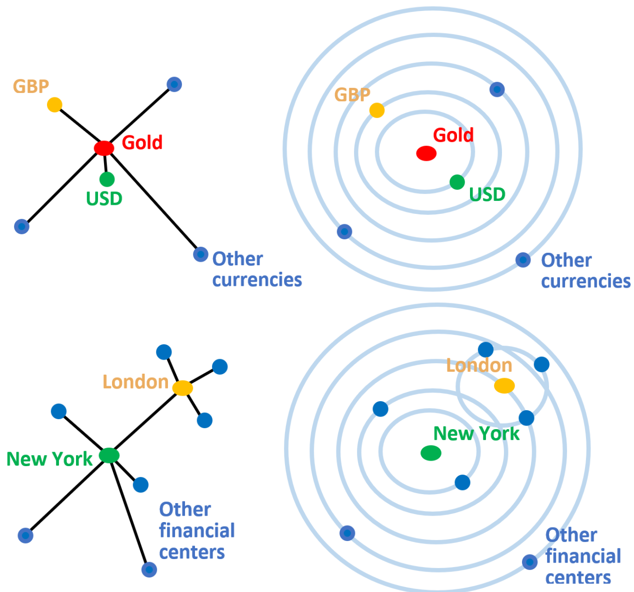

FIGURE 9 – Tree network (left) and stellar system diagrams (right), Gold exchange standard. International monetary system (upper), International financial system (lower).

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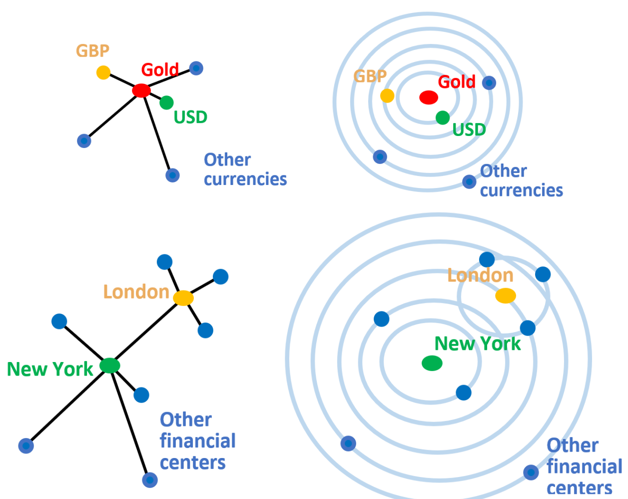

FIGURE 10 – Tree network model (left) and stellar system diagrams (right), Bretton Woods. International monetary system (upper), International financial system (lower).

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minance of New York as the premier financial center i.e IFS hub. The era is characterized by low transaction costs in foreign currency transactions because exchange rates were fixed, seen as IMS short distances ; but high transactions costs in international capital flows with widespread capital controls, seen as IFS long distances. This illustrates for the first time the possibility of a discordance in the density of the IMS and IFS layers.

The main stylized facts captured by the model are as follows. In the IMS layer, gold (the IMS hub) and the dollar (in the IMS core) standard become dominant, although the Bretton Woods agreements were initially based on two key currencies, the dollar and the pound sterling, Sterling being viewed as first line of defense for the dollar (Bordo et al., 2019). Sterling's position as a dominant currency ended after the 1967 devaluation and the crippling of the sterling area (Schenk, 1998). In this context, the discordance between low IMS distances and high IFS distances shows the dollar being used for trade, but with little capital flows because of capital controls. The position of the US as a financial intermediary (Despres et al., 1966) in the context of the widely believed at the time Triffin dilemma (Triffin, 1960), weakened the Gold/Dollar standard. This was the case especially after the 1965 US fiscal/monetary shocks of President Lyndon Baines Johnson's Great Society program and the Vietnam war. As the dollar came under increased attack capital controls lost their bite in the face of financial innovation, eg. in futures markets and trade invoicing (Marston, 1997). These developments illustrate the interactions between the regulatory component of the environment variable and its other components. At the same time, in the IFS layer New York cemented its position as key financial center (the IFS hub), with London in the IFS core still important as the reference financial center for the Sterling area along with the emergence of the Eurodollar market in London Schenk (1998); Naef (2022).

3.4 Managed Float

Figure 11 describes the Managed Float period. The model mainly highlights the central place of the US dollar in the IMS core and the financial center of New York as the IFS hub. This is in the context of the disappearance of an official link to gold in the IMS hub after the passage of the Second Amendment to the IMF Articles of Agreement in 1976. It also emphasizes the rise of plural regional financial centers (eg. in Tokyo, Hong Kong, Frankfurt, Paris) with none being dominant in the IMS core. Once again, a discordance is observed between relatively high transaction costs in foreign currency transactions, related to currency risk and low interoperability of banking systems i.e., IMS long distances ; and low transactions costs in deregulated international capital flows i.e. IFS short distances. The IMS layer illustrates that despite floating which creates domestic money sovereignty, the US Dollar (the IMS core) survives as the dominant currency for trade and financial flows, as documented in an extensive literature (e.g., Ilzetzki et al., 2022, 2019; Ito and McCauley, 2019). The IFS layer illustrates new regional networks with focal points in New York (IFS hub) and Europe (EMS/EMU, IFS core).

Generally speaking, this presentation of the historical development of IMS/IFS serves a dual purpose. On the one hand, it allows us to verify that the structure of the two-layer tree network model, with regime switchings related to an environmental variable, does indeed

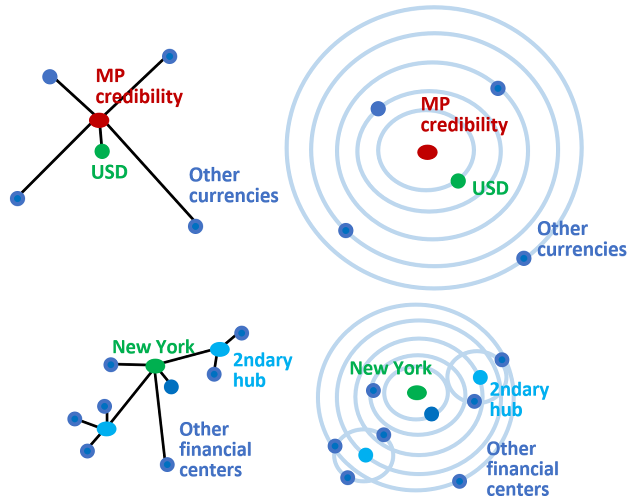

Figure 11 – Tree network model (left) and stellar system diagrams (right), Managed float. International monetary system (upper), International financial system (lower).

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provide a relevant description of the joint evolutions of the two systems. Secondly, it enables us to propose a succinct presentation that is simple and structured by a guiding thread which is appropriate to a comparative historical approach to a century and a half of monetary and financial history that is particularly dense in structural shocks. Both points allow us, as a conclusion of section 3, to propose a prospective analysis based on the modeling hypotheses previously retained ; and, in section **??**, to propose a theoretical model associated with these hypotheses.

3.5 The Future

The model at a glance described in Figure 12, corresponding to the assumptions of the two-layer regime-switching network model, could have the following characteristics. On the one hand, the persistence of the central place of the US dollar in the IMS core and the financial center in New York as the IFS hub, coexisting with rising regional currencies in the IMS core and financial centers in the IFS core. On the other hand, transaction costs in foreign exchange trades remaining relatively high, related to currency risk, creating IMS long distances, but possibly decreasing ; and low (and decreasing) transactions costs in international capital flows seen as IFS short distances, but possibly decreasing.

As regards the IMS layer, the most widely debated question in the literature today is that of the US dollar versus the Chinese Renminbi. In the absence of a major environmental shock (in the sense of the technological, institutional, geopolitical and governance variables), dollar dominance in the IMS core is likely to be assured Ilzetzki et al. (2022, 2019); Ito and McCauley (2019). This does not rule out a place for regional currencies, notably the Euro in the IMS core, with a truly multipolar system remaining unlikely (Eichengreen et al., 2022). As regards IMS distances, digital currency(ies) likely based on the dollar could reduce

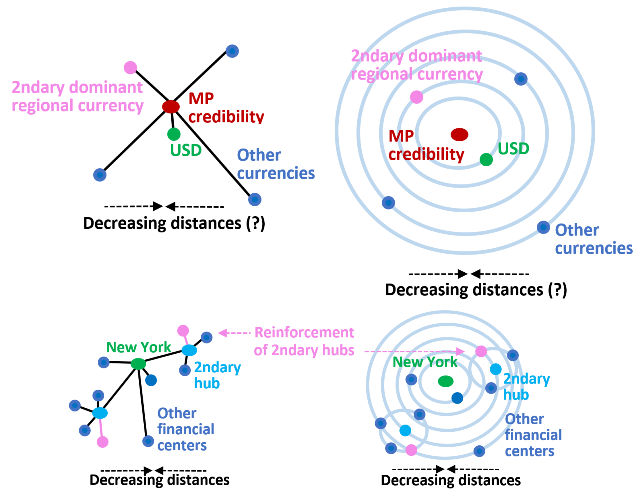

FIGURE 12 – Tree network model (left) and stellar system diagrams (right), prospective future developments. International monetary system (upper), International financial system (lower).

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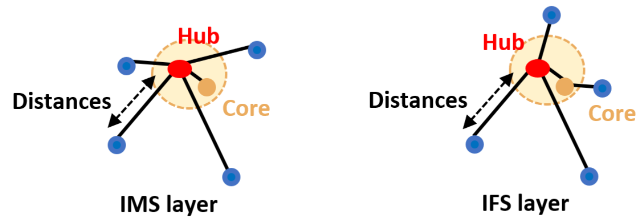
transaction costs in currencies by improving interoperability (Brunnermeier et al., 2019). In this context, the IMS layer would be characterized by growing regional networks in the IFS core but New York would still dominate as the IFS hub. Finally financial innovation, e.g. digitalization, would lead to new network patterns with decreasing transaction costs (i.e decreasing IFS distances).

4 A simple multiplex model with simultaneous IMS and IFS regime changes

4.1 Environment variable and transition variable of the regime-switching model

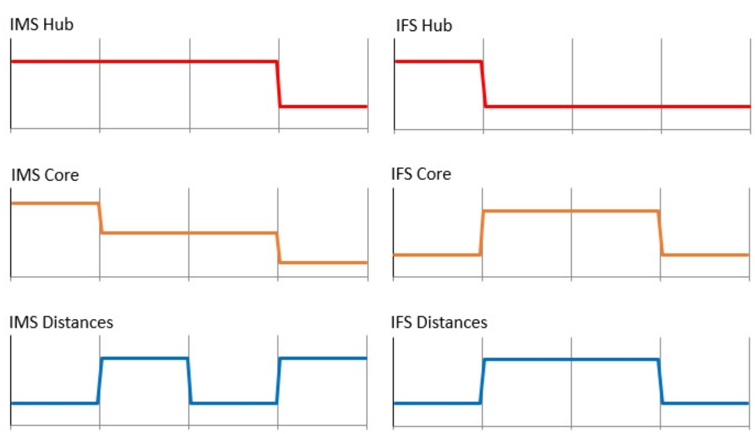
In this section we provide a formal description of the model, consisting of a dynamic two layers multiplex (*i.e.* a multi-layer network) : the first layer corresponds to the international monetary system, the second layer to the international financial system. Both the multiplex structure and assumptions about the structure of these layers are based on the reference literature in economic history and complex systems reviewed in Sections 2 and 3. Our contribution is twofold. On the one hand, we propose a simple model of the international monetary and financial systems, using and combining the original methods of multiplex graphs and non-linear regime-switching models. In addition, all the hypotheses of our model are directly testable, in particular the structure of graphs, their dynamic properties of stable regimes with simultaneous jumps, and the causal effect of the technological, institutional, geopolitical and regulatory environment on regime changes and graph structure in the different regimes.



(a)

$$\textbf{(b)}\quad \mathscr{D}_{M,t} = \begin{array}{cc} & j=0,\dots,n \\ i=0,\dots,n & \begin{pmatrix} 0 & \gamma_{Mt} d_{M\ 0,1\ t} & \gamma_{Mt} d_{M\ 0,2\ t} & & & \dots & \gamma_{Mt} d_{M\ 0,n\ t} \\ \gamma_{Mt} d_{M\ 1,0\ t} & 0 & 0 & & & \dots & 0 \\ \gamma_{Mt} d_{M\ 2,0\ t} & 0 & 0 & & & & \\ & & & 0 & & & \\ & & & & 0 & \dots & \dots \\ \dots & \dots & & & \dots & 0 & 0 \\ \gamma_{Mt} d_{M\ n,0\ t} & 0 & & & \dots & 0 & 0 \end{pmatrix} \end{array}$$

$$\mathscr{D}_{F,t} = \begin{array}{cc} & j=1,\dots,n \\ i=1,\dots,n & \begin{pmatrix} 0 & 0 & \dots & 0 & \gamma_{Ft} d_{F\ 1,k\ t} & 0 \\ 0 & 0 & \dots & & 0 & \gamma_{Ft} d_{F\ 2,k_1\ t} \\ \dots & \dots & 0 & 0 & \dots & \\ 0 & & 0 & 0 & & \dots \\ \gamma_{Ft} d_{F\ k,1\ t} & 0 & \dots & & 0 & \gamma_{Ft} d_{F\ k,n\ t} \\ 0 & \gamma_{Ft} d_{F\ k_1,2\ t} & & \dots & \gamma_{Ft} d_{F\ n,k\ t} & 0 \end{pmatrix} \end{array}$$



(c)

$$\textbf{(d)}\quad S_t = \begin{bmatrix} T_t \\ I_t \\ W_t \\ R_t \end{bmatrix} \longrightarrow \begin{cases} \gamma_{Mt} \ .\ A_M \ .\ \mathscr{D}_{M,t} = D_{M,t} & \text{(IMS layer)} \\ \gamma_{Ft} \ .\ A_{F,t} \ .\ \mathscr{D}_{F,t} = D_{F,t} & \text{(IFS layer)} \end{cases}$$

The two multiplex layers (IMS) and (IFS) consist of a hub, a core and other nodes connected to the hub and core by varying distances **(a)**. Their structure is described by the symmetrical matrices $\mathscr{D}_{M,t}$ and $\mathscr{D}_{F,t}$ where non-zero values correspond to the edges of the hub (in red) and core (in orange). The global distance component is shown in blue **(b)**. These variables are piecewise constant, with simultaneous jumps **(c)** determined by an environment variable S_t with four components : technological, institutional, geopolitical and regulatory **(d)**.

FIGURE 13 – Summary representation of the model

Each layer consists of a star network. The nodes correspond to currencies, in the international monetary system layer ; and to financial centers, in the financial system layer. As described above, the network has three distinctive characteristics : the node that occupies the hub position of the layers ("hub"), the nodes that are located at the heart of the network at a short distance from the hub (IMS layer "core") or as secondary hubs (IFS layer "core"), and the more or less dense or extensive nature of the network as a whole ("distances"). These three characteristics are a function of a four-variate environment variable describing the technological, institutional, geopolitical and regulatory environment, according to a non-linear relationship characterized by stable regimes. The geopolitical and regulatory environment vectors form the transition variables. In the event of an extreme geopolitical or regulatory event, the associated threshold is exceeded, and the hub, core and distance characteristics of each layer are affected by a simultaneous regime switching. The value of each of these characteristics after the shock depends on the four vectors of the technological, institutional, geopolitical and regulatory environment forming the environment variable. In the general case, and in the absence of extreme event, neither threshold is crossed and there is no regime switching. This overall structure is summarized in Figure 13.

The environment variable is denoted S_{it} where i corresponds to countries and t to time. It is composed of the four main environmental characteristics of international monetary and financial systems : technology (T_{it}), institutions (I_{it}), geopolitics and conflicts (W_{it}), and regulation (R_{it}), as follows :

$$S_{it} = \begin{bmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{bmatrix} \tag{1}$$

4.2 International Monetary System

The three characteristics of the IMS layer (see, for a summary, Figure A in the current Section ; and for a complete representation, Figures 7 and 8 in Section 2) are described by three specific matrices : the adjacency matrix A_M describes the position of the edges and thus designates the hub, the hierarchical distance matrix $\mathscr{D}_{\mathrm{M}}$ describes the hierarchy of distances from each node to the hub and thus characterizes the core, and the final distance matrix D_M describes the length of the edges and thus characterizes the extension of the network. All three matrices are square matrices of dimension $(n+1) \times (n+1)$. Index $i = 0$ corresponds to the dominant underlying asset C_0 of confidence in the system currencies, and indices $i = 1, \dots, n$ correspond to currencies $C_1, \dots, C_n$.

4.2.1 Adjacency matrix

The structure of the adjacency matrix A_M is as follows :

$$A_M = \begin{array}{cc} & j=0,...,n \\ \text{i=0,...,n} & \begin{pmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & & & ... & 0 \\ 1 & 0 & 0 & & & & \\ 1 & & & 0 & & & \\ 1 & & & & 0 & ... & ... \\ 1 & ... & & & ... & 0 & 0 \\ 1 & 0 & & & ... & 0 & 0 \end{pmatrix} \end{array} \tag{2}$$

That is :

$$\begin{gathered} a_{M\ i,j} = 1 \text{ if } i = 0 \text{ or } j = 0,\ (i,j) \neq (0,0) \\ a_{M\ i,j} = 0\ \forall\ i \neq 0 \text{ or } j \neq 0 \end{gathered} \tag{3}$$

As the network is undirected, the matrix is symmetrical, like the other two matrices describing the IMS structure.

Based on the literature discussed above, we hypothesize that the asset $C_{M\ 0,t}$ that underlies confidence in the currencies of the international monetary system is unique in each time t. A_M is therefore unchanged over time : each of the currencies is uniquely linked to this specific asset. When a regime switching occurs, this asset is likely to change, as follows :

$$\begin{gathered} C_{M\ 0,t} = f_M\left(T_t, I_t, W_t, R_t\right) \\ C_{M\ 0,t} = \{G, MP, OT\} \end{gathered} \tag{4}$$

$C_{M\ 0,t}$ takes three possible values over the period of study : gold (G), monetary policy credibility (MP). In order to propose as general a specification as possible, we include a third possible value for $C_{M\ 0,t}$, corresponding to neither of the two values observed so far, that is "other" (OT). The use of a different dataset for the study of earlier or prospective systems does not change the structure of the adjacency matrix insofar as the asset which underlies confidence is always unique and indexed 0. The non-linear form of function $f_M\left(T_t, I_t, W_t, R_t\right)$ describing the evolution of $C_{M\ 0,t}$ in relation to the geopolitical W_t and regulatory R_t components of the environment variable is described in more detail below.

4.2.2 Hierarchical distance matrix

The hierarchical distance matrix $\mathscr{D}_{\mathrm{M,t}}$ establishes the hierarchy of distances corresponding to the edges of the adjacency matrix. Its structure is as follows :

$$
\mathscr{D}_{M,t} = \begin{array}{cc} & j=0,...,n \\ \text{i=0,...,n} & \begin{pmatrix} 0 & d_{M\ 0,1\ t} & d_{M\ 0,2\ t} & & & ... & d_{M\ 0,n\ t} \\ d_{M\ 1,0\ t} & 0 & 0 & & & ... & 0 \\ d_{M\ 2,0\ t} & 0 & 0 & & & & \\ & & & 0 & & & \\ & & & & 0 & ... & ... \\ ... & ... & & & ... & 0 & 0 \\ d_{M\ n,0\ t} & 0 & & & ... & 0 & 0 \end{pmatrix} \end{array} \tag{5}
$$

$\mathscr{D}_{\mathrm{M,t}}$ describes the structure of the core at time t, as follows :

$$
\begin{gathered}
d_{M\ i,0\ t} = d_{M\ 1,0\ t} \\
d_{M\ i,0\ t} = g_M\left(T_t, I_t, W_t, R_t\right) \\
d_{M\ i,0\ t} = \left\{\underline{d}_M, \overline{d}_M\right\},\ \forall i \neq 0 \\
\underline{d}_M \in \left[\underline{d}_{Ml}, \underline{d}_{Mu}\right] \\
\overline{d}_M \in \left[\overline{d}_{Ml}, \overline{d}_{Mu}\right]
\end{gathered} \tag{6}
$$

$$
\text{with } 0 < \underline{d}_{Ml} < \underline{d}_{Mu} < 1 < \overline{d}_{Ml} < \overline{d}_{Mu}
$$

$\forall i \neq 0$, the distance to the hub $d_{M\ i,0\ t} = d_{M\ 0,i\ t}$ is established in two possible intervals. $\underline{d}_M$ characterizes distances within the interval $[\underline{d}_{Ml}, \underline{d}_{Mu}]$. Currencies characterized by these short distances make up the core, i.e. are dominant in the functioning of the IMS. During the period under study, there are at most two at a time : the Pound sterling and the US dollar, during the Interwar and Bretton-Woods periods. In general, the dominant currency is unique. $\overline{d}_M$ characterizes long distances, within the the interval $\left[\overline{d}_{Ml}, \overline{d}_{Mu}\right]$. Currencies characterized by these long distances are outside the core, i.e. not dominant. These are all other currencies. When a switching regime occurs, the hierarchical structure of distances, and therefore the dominant currency, is likely to change. In the absence of regime change, the hierarchical distance matrix remains unchanged from one period to the next.

4.2.3 Final distance matrix

The final distance matrix $\mathrm{D}_{\mathrm{M,t}}$ describes the edges length, or network dimension, in the IMS layer. This dimension depends on the hierarchy established in the hierarchical distance matrix $\mathscr{D}_{\mathrm{M,t}}$, and on a global distance coefficient γ_t taking high values when transaction costs are high and low values when transaction costs are low, i.e. the following structure :

$$
\mathrm{D}_{\mathrm{M,t}} = \gamma_{Mt} \mathscr{D}_{\mathrm{M,t}} \tag{7}
$$

$$
\mathrm{D}_{M,t} = \begin{array}{cc} & j=0,...,n \\ \mathrm{i=0,...,n} & \begin{pmatrix} 0 & \gamma_{Mt} d_{M\ 0,1\ t} & \gamma_{Mt} d_{M\ 0,2\ t} & & & ... & \gamma_{Mt} d_{M\ 0,n\ t} \\ \gamma_{Mt} d_{M\ 1,0\ t} & 0 & 0 & & & ... & 0 \\ \gamma_{Mt} d_{M\ 2,0\ t} & 0 & 0 & & & & \\ & & & 0 & & & \\ & & & & 0 & ... & ... \\ ... & ... & & & ... & 0 & 0 \\ \gamma_{Mt} d_{M\ n,0\ t} & 0 & & & ... & 0 & 0 \end{pmatrix} \end{array} \tag{8}
$$

$$
\begin{gathered}
\gamma_{Mt} = h_M \left(T_t, I_t, W_t, R_t\right) \\
\gamma_{Mt} = \left\{\underline{\gamma}_{Mt}, \overline{\gamma}_{Mt}\right\} \\
\underline{\gamma}_{Mt} \in \left[\underline{\gamma}_{Ml}, \underline{\gamma}_{Mu}\right] \\
\overline{\gamma}_{Mt} \in \left[\overline{\gamma}_{Ml}, \overline{\gamma}_{Mu}\right] \\
\underline{\gamma}_{Ml} < \underline{\gamma}_{Mu} < \overline{\gamma}_{Ml} < \overline{\gamma}_{Mu}
\end{gathered} \tag{9}
$$

The γ_{Mt} coefficient is set in two possible value ranges. $\underline{\gamma}_{Mt}$ corresponds to a low value, within the range $\left[\underline{\gamma}_{Ml}, \underline{\gamma}_{Mu}\right]$. This interval corresponds to relatively low transaction costs under persistently fixed exchange rate regimes, i.e. short distances and a dense network. $\overline{\gamma}_{Mt}$ corresponds to a relatively high value, within the interval $[\overline{\gamma}_{Ml}, \overline{\gamma}_{Mu}]$. This interval corresponds to high transaction costs under flexible or non-persistently fixed exchange rate regimes, i.e. long distances and an extended network. When a regime switching occurs, the γ_{Mt} coefficient and the hierarchical structure of distances are likely to change at the same time. In the absence of regime change, the coefficient γ_{Mt} and the hierarchical structure are unchanged from one period to the next.

4.2.4 Regime switching

IMS layer regime switchings are therefore described as follows :

$$
\text{if} \left\{ \begin{array}{c} W_t - W_{t-1} \geq W^* \\ \text{or } R_t - R_{t-1} \geq R^* \end{array} \right. \quad \Rightarrow \left\{ \begin{array}{r} C_{M\ 0,t} = f_M(S_t) = f_M \begin{pmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{pmatrix} \\ d_{M\ i,0\ t} = d_{M\ 1,0\ t} = g_M\left(S_t\right) = g_M \begin{pmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{pmatrix}, \ \forall i = 1, ..., n \\ \gamma_{Mt} = h_M\left(S_t\right) = h_M \begin{pmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{pmatrix} \end{array} \right.
$$

$$
\text{if} \left\{ \begin{array}{c} W_t - W_{t-1} < W^* \\ \text{and } R_t - R_{t-1} < R^* \end{array} \right. \quad \Rightarrow \begin{cases} C_{0,t} = C_{0,t-1} \\ d_{M\ i,1\ t} = d_{M\ i,t-1}, \ \forall i = 1, ..., n \\ \gamma_{M\ t} = \gamma_{M\ t-1} \end{cases}
$$

(10)

In other words, crossing the extreme event variation threshold W^* for the geopolitical component W_t of the environment variable (respectively, the variation threshold R^* for the regulatory component R_t) conditions a regime switching. When it occurs, we observe a simultaneous jump in the nature of the asset making up the hub $C_{0,t}$, i.e. the reference asset ; in the hierarchy of distances $d_{M\ i,0\ t} = d_{M\ 0,i\ t}$ specifying the core, i.e. the dominant currencies ; and in the γ_{Mt} coefficient of global distances, i.e. the global level of transaction costs. For each of these variables, the value taken after the regime switching depends on the four components of the environment variable. We note that this value may be unchanged for some variables, as observed for example for the hub (gold) during the first three periods described above, or for the core between the second and third periods (Sterling), but that their jumps are always simultaneous. Based on observation of IMS developments over the last century and a half, the geopolitical W_t and regulatory R_t components of the environment variable are the only threshold variables in the model. Along with the technological T_t and institutional I_t components, they condition the values taken after the regime change by the core, the hierarchy of distances, and the coefficient of global distances.

Apart from regime changes, the hub, distance hierarchy and overall distance coefficient are stable.

4.3 International financial system

Like those of the IMS layer, the three characteristics of the IFS layer (see Figure 13) are described by three specific matrices : the adjacency matrix A_F describes the position of the edges and thus designates the hub, as the most connected financial center ; and the core, as local hubs. The hierarchical distance matrix $\mathscr{D}_{\mathrm{F}}$ describes the hierarchy of distances from each node to the hub, and the final distance matrix D_F describes the length of the edges and thus characterizes the extension of the network. The combination of those two distance matrices characterizes global distances within the layer. In other terms, based on the previously reviewed theoretical and empirical literatures both in monetary and financial economics and in complex networks, the core of the IFS layer is defined by its connectivity, unlike the IMS layer where it is defined by its short distance from the hub. All three matrices are square matrices of dimension $n \times n$. The indexing is similar to that of the IMS layer matrices, except that it starts at 1 (i.e. $i = 1, \dots, n$), with the graph including only countries (financial centers), whereas the graph of the SFI layer includes in addition to countries (currencies), the reference asset underlying confidence in the system, indexed 0. Countries $C_1, \dots, C_n$ are indexed in the same order than that of the IMS layer.

4.3.1 Adjacency matrix

The structure of the adjacency matrix A_F is as follows, in the example where the financial center indexed $i = n - 1$ is the hub, and $i = n$ is the core to which $i = 2$ is directly linked :

$$A_F = \begin{array}{cc} & i = 1, ..., n \\ \text{i=0,...,n} & \begin{pmatrix} 0 & 0 & ... & 0 & 1 & 0 \\ 0 & 0 & ... & & 0 & 1 \\ ... & ... & 0 & 0 & 1 & \\ 0 & & 0 & 0 & 1 & ... \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & & ... & 1 & 0 \end{pmatrix} \end{array} \tag{11}$$

As before, the network is undirected and the A_F matrix, like the other two matrices describing the IMS structure, is symmetrical. Unlike the IMS, where the underlying asset of confidence is added to the currencies in the graph and is always indexed 0, in the case of the IFS, the adjacency matrix is not unchanged over time : the financial center C_k that constitutes the hub is not always the same, and its indexation k_t can in principle correspond to any value in the interval $1, ..., n$, i.e. all the financial centers in the system. In practice, the period under study shows only two : London and New York. The same applies to the financial center(s) C_{k_1}, C_{k_2}, etc., which form the core : any financial center can in principle become the core or part of it when a regime switching occurs. Over the period studied, the core is composed of London as the sole secondary hub during the Interwar and Bretton Woods eras ; and several financial centers in the periods of strong financial integration represented by the 1st and 2nd eras of globalization.

The assumption that any financial center can, in principle, become the hub or the core following a regime change is aimed to keep the model as general as possible, so that it can be used to study earlier systems, or the prospects for the current system. Within this general framework, on the basis of the evolutions of the IMS and IFS described in Sections 1 to 3 and the literature on currency dominance, we hypothesize that the IFS hub corresponds to the currency or one of the currencies of the IMS core, i.e. $d_{M\ k,0\ t} = \underline{d}_M$. In view of the same facts and literature, a financial center belonging to the IMS core is a necessary condition for it to be an IFS hub, but not necessarily for it to belong to the IFS core.

So, nodes connected to the hub via the core node C_{k_1} being denoted $C_{k_{1_a}}$, $C_{k_{1_b}}$, etc., the edges connecting the hub are described by :

$$\begin{gathered} a_{F\ i,j} = 1 \text{ if } i = k \text{ or } j = k \text{ and } i, j \neq k_{1_a}, k_{1b}, ...,\ (i,j) \neq (0,0) \\ a_{F\ i,j} = 0\ \forall\ i \neq k \text{ or } j \neq k \\ \text{with } k\ \in\ i\ / d_{M\ k,0\ t} = \underline{d}_M \end{gathered} \tag{12}$$

and the edges connecting core k_1 by :

$$a_{F\ i,j} = 1 \text{ if } i = k_1 \text{ and } j = k_{1_a}, k_{1_a}, ...; \text{or } i = k_{1_a}, k_{1_a}, ...\ ; \text{and } j = k_1 \tag{13}$$

The same applies if the core is made up of several nodes $k_1,\ k_2$, etc. There are no other edges in the adjacency matrix : all other values in the adjacency matrix are therefore zero.

When a regime switching occurs, the financial centers that constitutes the hub and the cores are likely to change, as follows :

$$\begin{gathered} (C_{F\ k,t}, C_{F\ k_{1,t}},\ C_{F\ k_{2,t}}, ...) = f_F\,(T_t, I_t, W_t, R_t) \\ C_{F\ k,t} = \{C_1, ..., C_n\ /\ d_{M\ k,0\ t} = \underline{d}_M\} \\ C_{k_{1,t}},\ C_{k_{2,t}}, ... = \{C_1, ..., C_n\} \end{gathered} \tag{14}$$

The non-linear form of function $f_F\,(T_t, I_t, W_t, R_t)$ describing the evolution of $C_{F\ k,t}$ and the $C_{k_{1,t}},\ C_{k_{2,t}}, ...$ with respect to the geopolitical W_t and regulatory R_t components of the environment variable is described in more detail below.

4.3.2 Hierarchical distance matrix

The hierarchical distance matrix $\mathscr{D}_{\mathrm{F,t}}$ establishes the hierarchy of distances corresponding to the edges of the adjacency matrix. Its structure is as follows, still in the example where the financial center indexed $i = n-1$ is the hub, and $i = n$ is the core to which $i = 2$ is directly linked :

$$\mathscr{D}_{F,t} = \begin{array}{cc} & j = 1, ..., n \\ \mathrm{i=1,...,n} & \begin{pmatrix} 0 & 0 & ... & 0 & d_{F\ 1,k\ t} & 0 \\ 0 & 0 & ... & & 0 & d_{F\ 2,k_1\ t} \\ ... & ... & 0 & 0 & ... & \\ 0 & & 0 & 0 & & ... \\ d_{F\ k,1\ t} & 0 & ... & & 0 & d_{F\ k,n\ t} \\ 0 & d_{F\ k_1,2\ t} & & ... & d_{F\ n,k\ t} & 0 \end{pmatrix} \end{array} \tag{15}$$

$\mathscr{D}_{\mathrm{F,t}}$ describes the connexions to the hub and core(s) at time t for non-zero elements of the adjacency matrix $A_{F,t}$:

$$
\begin{gathered}
d_{F\ i,k\ t} = d_{F\ k,i\ t} \\
d_{F\ i,k_1\ t} = d_{F\ k_1,i\ t} \\
d_{F\ i,k_2\ t} = d_{F\ k_2,i\ t} \\
\dots \\
\\
(d_{F\ i,k\ t}, d_{F\ i,k_1\ t}, d_{F\ i,k_2\ t}, \dots) = g_F\left(T_t, I_t, W_t, R_t\right) \\
(d_{F\ i,k\ t}, d_{F\ i,k_1\ t}, d_{F\ i,k_2\ t}, \dots) = \left\{\underline{d}_F, \overline{d}_F\right\},\ \forall i \neq 0 \\
\underline{d}_F \in \left[\underline{d}_{Fl}, \underline{d}_{Fu}\right] \\
\overline{d}_F \in \left[\overline{d}_{Fl}, \overline{d}_{Fu}\right] \\
\\
\text{with } 0 < \underline{d}_{Fl} < \underline{d}_{Fu} < 1 < \overline{d}_{Fl} < \overline{d}_{Fu} < 1
\end{gathered}
\tag{16}
$$

The distance of financial center i to the hub $d_{F\ i,k\ t} = d_{F\ k,i\ t}$, or the distance $d_{F\ i,k_1\ t} = d_{F\ k_1,i\ t}$ to the core k_1 in the case where it is not directly connected to the hub, is established in two possible intervals. $\underline{d}_F$ characterizes distances within the interval $[\underline{d}_{Fl}, \underline{d}_{Fu}]$. The financial centers characterized by these short distances are closely connected to one of the dominant financial centers, i.e. are themselves important in the operation of the IFS. $\overline{d}_F$ characterizes long distances within the interval $\left[\overline{d}_{Fl}, \overline{d}_{Fu}\right]$. The financial centers characterized by these long distances are remote from the dominant centers.

Note that the core of the IFS layer is defined by its connectivity, *i.e.* more than one edge in the adjacency matrix, unlike the IMS layer where it is defined by its small distance from the hub. In other words, $d_{F\ k,k_1\ t} = d_{F\ k_1,k\ t}$ does not necessarily belong to the interval $[\underline{d}_{Fl}, \underline{d}_{Fu}]$.

When a regime switching occurs, the hierarchical structure of distances, and therefore the financial centers in the close neighborhood of dominant centers, is likely to change. In the absence of regime switching, the hierarchical distance matrix remains unchanged from one period to the next.

4.3.3 Final distance matrix

The final distance matrix $\mathrm{D_{F,t}}$ describes the edge length, or network dimension, in the IFS layer. This dimension depends on the hierarchy established in the hierarchical distance matrix $\mathscr{D}_{\mathrm{F,t}}$, and on a global distance coefficient γ_t that is high when transaction costs are high and low when transaction costs are low, i.e. the following structure :

$$
\mathrm{D_{F,t}} = \gamma_{Ft}\mathscr{D}_{\mathrm{F,t}} \tag{17}
$$

$$
\mathscr{D}_{F,t} = \begin{array}{cc} & j=1,...,n \\ \rotatebox{90}{i=1,...,n} & \begin{pmatrix} 0 & 0 & ... & 0 & \gamma_{Ft} d_{F\ 1,k\ t} & 0 \\ 0 & 0 & ... & & 0 & \gamma_{Ft} d_{F\ 2,k_1\ t} \\ ... & ... & 0 & 0 & ... & \\ 0 & & 0 & 0 & & ... \\ \gamma_{Ft} d_{F\ k,1\ t} & 0 & ... & & 0 & \gamma_{Ft} d_{F\ k,n\ t} \\ 0 & \gamma_{Ft} d_{F\ k_1,2\ t} & & ... & \gamma_{Ft} d_{F\ n,k\ t} & 0 \end{pmatrix} \end{array} \tag{18}
$$

$$
\begin{gathered}
\gamma_{Ft} = h_F\left(T_t, I_t, W_t, R_t\right) \\
\gamma_{Ft} = \left\{\underline{\gamma}_F, \overline{\gamma}_F\right\} \\
\underline{\gamma}_F \in \left[\underline{\gamma}_{Fl}, \underline{\gamma}_{Fu}\right] \\
\overline{\gamma}_F \in \left[\overline{\gamma}_{Fl}, \overline{\gamma}_{Fu}\right] \\
\underline{\gamma}_{Fl} < \underline{\gamma}_{Fu} < \overline{\gamma}_{Fl} < \overline{\gamma}_{Fu}
\end{gathered} \tag{19}
$$

The γ_{Ft} coefficient is set in two possible ranges. $\underline{\gamma}_F$ corresponds to a low value, in the $\left[\underline{\gamma}_{Fl}, \underline{\gamma}_{Fu}\right]$ range. This interval corresponds to low transaction costs in the context of a low level of regulation of financial activity, i.e. short distances and a dense network, as in the 1st and 2nd eras of globalization. $\overline{\gamma}_F$ corresponds to a high value, within the interval $[\overline{\gamma}_{Fl}, \overline{\gamma}_{Fu}]$, in the context of a high level of regulation, as in the Interwar and Bretton Woods eras. This interval corresponds to high transaction costs under a high level of regulation of financial activity, i.e. long distances and an extensive network. When a regime switching occurs, both the γ_{Ft} coefficient and the hierarchical distance structure are likely to change at the same time. In the absence of a regime switching, the γ_{Ft} coefficient and the hierarchical structure are unchanged from one period to the next.

4.3.4 Regime switchings

The regime switching of the IFS layer is therefore described as follows :

$$\text{if}\left\{\begin{array}{c} W_t - W_{t-1} \geq W^* \\ \text{or } R_t - R_{t-1} \geq R^* \end{array}\right. \Rightarrow \left\{\begin{array}{c} (C_{F\ k,t}, C_{k_{1,t}},\ C_{k_{2,t}}, ...) = f_F\begin{pmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{pmatrix} \\ \\ (d_{F\ i,k\ t}, d_{F\ i,k_1\ t}, d_{F\ i,k_2\ t}, ...) = (d_{F\ k,i\ t}, d_{F\ k_1,i\ t}, d_{F\ k_2,i\ t}, ...) \\ = g_F\begin{pmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{pmatrix} \forall i = 1, ..., n \\ \\ \gamma_{Ft} = h_F\left(S_t\right) = h_F\begin{pmatrix} T_{it} \\ I_{it} \\ W_{it} \\ R_{it} \end{pmatrix} \end{array}\right.$$

$$\text{if}\left\{\begin{array}{c} W_t - W_{t-1} < W^* \\ \text{and } R_t - R_{t-1} < R^* \end{array}\right. \Rightarrow \left\{\begin{array}{c} (C_{F\ k,t}, C_{k_{1,t}},\ C_{k_{2,t}}, ...) \\ = (C_{F\ k,t-1}, C_{k_{1,t-1}},\ C_{k_{2,t-1}}, ...) \\ \\ (d_{F\ i,k\ t}, d_{F\ i,k_1\ t}, d_{F\ i,k_2\ t}; ...) \\ = (d_{F\ i,k\ t-1}, d_{F\ i,k_1\ t-1}, d_{F\ k_2,i\ t}, ...) \\ \forall i = 1, ..., n \\ \\ \gamma_{Ft} = \gamma_{F\ t-1} \end{array}\right.$$

(20)

The regime switching of the IMS and IFS layers is simultaneous and associated with the crossing of the extreme event threshold W^* for the geopolitical component W_t of the environment variable (respectively, with the threshold R^* for the regulatory component R_t). This regime switching causes a jump in the financial centers constituting the hub $C_{F\ k,t}$ and the core $C_{k_1},\ C_{k_2},\ ...$; and in the hierarchy of distances $(d_{F\ i,k\ t}, d_{F\ i,k_1\ t}, d_{F\ i,k_2\ t}, ...) = (d_{F\ k,i\ t}, d_{F\ k_1,i\ t}, d_{F\ k_2,i\ t}, ...)$ and the γ_{Ft} coefficient of overall distances, associated to the level of transaction costs.

For each of these variables, the value taken after the regime switching depends on the four components of the environment variable. As for the IMS layer, this value may be unchanged for some variables, as observed for example for New-York as the hub of the last three periods, or for London as the core of the second and third periods. The global distance coefficient is also unchanged (and high) between the second and third periods. Apart from regime changes, the hub, core and global distances are stable.

4.4 Discussion

The hypotheses derived from the analogy allow us to propose an original theoretical model of the long-term developments in the international monetary and financial systems. The period discussed in the previous sections goes back to the last century and a half, but the theoretical model is sufficiently general to be used over a longer period, or for prospective analysis. All the model assumptions can be tested. The existing literature documents that time series (in particular, of prices and trade volumes) associated with each of the multiplex layers allow to produce an empirical measure of their hub, core and distance characteristics. The empirical validation of the model could, then, follow three main stages.

The first step is to validate the nature of the regime-switching model. On the basis of the stylized facts and reference literature, we propose a model with stable regimes and simultaneous regime switchings in the network structures of both layers. It should be noted that the multiplex actually enables the study of doubly simultaneous regime shifts : for each of the layers, and for the three variables describing the network structures within layers. The second stage of empirical validation would consist in defining a set of proxies for the components of the environment variable, and checking that the crossing of thresholds for the geopolitical and regulatory components is indeed associated with regime switchings in the multiplex. The third step would consist in implementing non-linear regressions to characterize the relationship between the components of the environment variable and the hub, core and layer structure variables.

The empirical validation would then enable us to gain additional understanding of the determinants of long-term trends in the simultaneous structures of the IMS and IFS, particularly with regard to dominant currencies and financial centers. It would also be possible to build scenarii of future developments. For example, on the basis of different evolutions in the components of the environment variable that are deemed plausible, the empirical estimation of the model parameters would make it possible to document, in an original way and taking into account the non-linearities of the underlying model, different scenarii for the dominance of the US dollar.

5 Conclusion : some lessons for the future from the analogy

It should be clear that we do not consider that the primarily deterministic character of the organization of stellar systems can strictly be transposed to the IMS/IFS, whose shapes depend on unpredictable human decisions. However, the analogy between Copernican-type stellar systems and IMS/IFS offers an interesting modelling approach. On the one hand, it provides a simple, stylized reading of monetary and financial history over a century and a half, offering a framework for prospective analysis. On the other hand, it allows us to describe the corresponding theoretical model in formal terms. This model, based on a novel combination of a multi-layer network model and a model of regime switching conditioned by a multi-dimensional environmental variable, is fully testable.

Beyond the model, by generalizing the analogy, three main lessons can be drawn. The first lesson is that the center of the system is not necessarily where we think it is. This first lesson, directly linked to the transition from the geocentric to the heliocentric model , echoes the main current, but also more recurrent, concerns regarding the structure of the IMS/IFS. More specifically, in the case of the IMS, we argue that the hub of the system is not one of the currencies, but the underlying asset of confidence. Under these conditions, the dominance of the US dollar in the IMS seems to be assured for the moment as currency dominance is essentially stable over long eras bounded by environmental shocks of exceptional magnitude. This does not mean that the future may not be different. In the case of the IFS, we agree with the work of economic historians who stress that, while persistence is a key feature of the system, it should not be overestimated (e.g., Eichengreen2018). The driving force behind the dynamics of financial integration is not necessarily solely the US. For example, financial integration has been driven by European integration since the 1950s.

The second lesson proceeds from a broad generalization of the analogy. So far, we have reasoned within the general pattern of a single heliocentric system. Modern astrophysics studies an infinite number of stellar systems. This would correspond to a strong form of multicentrism, describing systems operating essentially unrelated to each other as opposed to a weaker form of multicentrism, described by our proposed model, in which there may be secondary dominant currencies and financial centers, but within the same connected graph. The difference between the two is essential in assessing the emergence of the Remimbi in the IMS, for example. We can thus imagine that after the emergence of the currency as a regional hub in the IMS, the structure of the system could evolve towards a true multi-polarization with disconnected graphs.

The third and last lesson from the analogy is related to the fact that, in addition to the life cycles of stars, the dimensions of the universe radically change over time, with the Big bang, the expansion of the solar system, and eventually the contraction of the universe. As with multi-centrism, the variation over time of the system dimensions could then be understood in the sense of the medium term, as in our proposed model, which mimics the life cycle of stars. This reading corresponds with distances between the IMS currencies changing over time with the transaction costs associated with the nature of the exchange rate regimes, currency risk and interoperability of banking systems ; and distances between financial centers of the IFS also evolving, along the U-shaped financialization curve (Obstfeld and Taylor, 2004; Bastidon et al., 2023). In the very long term, these variations do not exclude more radical variations corresponding to the overall dynamics of the capitalist system.

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