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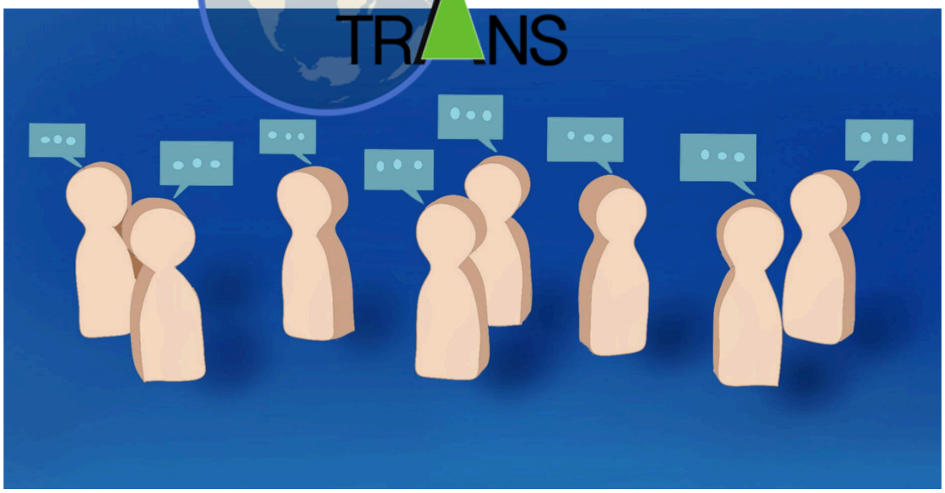

WorldTrans - Transparent Assessments for Real People

WorldTrans Deliverable Report

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Table of Contents:

List of Figures:

List of Tables:

Table 1: Abbreviation list

Acronym	**Full Name**
GDP	Gross Domestic Product
IAM	Integrated Assessment Model
SLR	Sea Level Rise
STA	Surface Temperature Anomaly

In brief…..

What we did:

We built a novel Schumpeterian, disequilibrium-based economy module for the FRIDA IAM, integrating monetary and financial dimensions to capture key feedback loops between socio-economic and natural systems. Its highly aggregate structure enables exploration of short- and long-term economic cycles – including hysteresis effects – sensitive to climate events, by simulating the production, financial, and government sectors as interlinked representative agents. Moreover, it is stock-flow consistent, capturing the movement and accumulation of financial resources within and between sectors. The result is a comprehensive framework for policy experimentation that includes mechanisms of innovation, investment, and economic shocks, and how they affect nominal and real economic outcomes over a century-long time horizon.

Why we did it:

Building an entirely new economic module allows us to achieve analytical objectives that existing IAM economic modules could not support. Choosing a disequilibrium-based framework allows the simulation of short-term interactions between natural and socio-economic domains with long-term consequences. Integrating Monetary and financial mechanisms explicitly captures processes like credit creation, financial instability, and creative destruction, which are rarely considered by traditional IAMs. This approach ensures that key climate-relative financial risks, including investment failures and macrofinancial instability, are reflected in our analysis.

The module's design also enhances its relevance for climate related policy-making by enabling a broad range of interventions, leveraging central banking, finance and government. Additionally, the transparency afforded by the System Dynamics approach allows researchers and stakeholders to better understand the modules assumptions, limitations, and mechanisms. Ultimately, this design supports the WorldTrans project's goals, broadens the integrated assessment field, and serves as a tool to inform effective climate policies.

We think this framework and toolbox will have an impact because

By linking monetary and financial mechanisms with climate and natural feedback, the FRIDA model opens new avenues for policy-relevant insights. Its politically neutral Schumpeterian focus on innovation and creative destruction offers a different lens from more conventional IAMs, by shedding light on how short-term shocks, endogenous credit creation, and innovation can alter long-term climate outcomes. The transparency of its structure and the flexibility of the disequilibrium framework ensure that stakeholders, including policy-makers and researchers, can engage with its assumptions and results, which potentially leads to more nuanced discussions and stronger climate strategies.

Insights and Next Steps

Building a novel economic module largely confirmed our initial assumptions, namely the relevance of including financial and monetary mechanisms within coupled natural/socio-economic feedback loops. It also provided us with a wide array of instruments supporting policy-implementation scenarios, despite the highly aggregate nature of the model. Finally, it helps identify the specific contributions that FRIDA brings to the IAM community, and its value for researchers and policy-makers alike.

While the module is functionally complete, small but significant expansions are already planned for the future First, we aim to integrate a number of inequality measures, drawn from the Sustainable Development Goals suite of indicators. Then, we plan to expand available options for policy funding, integrating central bank monetization and expanding on taxation options. We also aim to endogenize more aspects of the government sector, to improve the ability of FRIDA to capture the emergent dynamics linked with the demographic shift which is expected to dominate the second half of the current century. Finally, we aim to integrate within the main FRIDA version an experimental fork which includes private and public eco-innovation, further expanding the scope of applicability of the model.

Besides these planned changes, a number of expansions are possible beyond the scope of the current WorldTrans project. Some modest forks, focused on evaluating post-growth alternatives and more fragile financial configurations, are likely to be developed this year. More ambitious model development projects, such as the integration of wealth portfolio management dynamics and equity markets, would require the drafting of new research proposals. While future development is always uncertain, the current research team is dedicated to use and improve FRIDA further, involving more members of the research community in the process.

Executive Summary:

This report presents the FRIDA 2.0 Economy Module, developed to advance the integration of socio-economic and natural systems for long-term climate policy analysis. FRIDA, a system dynamics integrated assessment model (IAM), simulates interactions between multiple global systems over a century-long time horizon. The Economy Module, now functionally complete, builds on a Schumpeterian, disequilibrium-based, and monetary framework that enables the analysis of short-term cycles and their long-term consequences within climate constraints. Building on version 1.0, its new submodules – covering labour, innovation and central banking – enhance its realism and policy experimentation options.

The module is part of a broader network of seven interconnected FRIDA modules, receiving inputs from the climate, Land Use and Agriculture, and Energy modules while providing outputs to Demographics, Resources, Energy, and Behavioural Change. Internally, the Economy Module consists of seven interconnected submodules covering key macroeconomic processes: Circular Flow, Finance, Innovation, Government, Employment, GDP, and Inflation. The modules are purposely highly aggregate for conceptual clarity and computational efficiency, focusing on feedback mechanisms between households, firms, the financial system, and governments.

A core achievement of the module is its ability to endogenously generate oscillatory cycles in macroeconomic indicators such as GDP, unemployment, wages, and inflation. These cycles are emergent of the feedback processes driven by credit provisioning, labour market dynamics, consumption patterns, and fiscal and monetary policy. For example, the credit cycle creates alternating periods of growth and contraction as changing lending standards and interest rates respond to default rates. The interaction of these cycles with climate impacts introduces to the field consideration of financial instability, and how short-term disruptions have long-term economic outcomes.

The module's design supports scenario-based experimentation, offering policymakers and researchers a range of intervention options. These include adjustments of central bank inflation and unemployment targets, fiscal strategies, and alternate mechanisms for financing the green transition. Furthermore, unlike many existing IAMs, FRIDA integrates monetary and financial mechanisms that influence both nominal and real economic performance, which greatly improves relevance for macroeconomic and climate-related policy design.

Looking forward, the module will undergo further development. Planned enhancements include integrating inequality measures, expanding fiscal policy options, and further endogenizing government processes to reflect demographic changes. The current version

also provides a robust foundation for future research and specialised adaptations, enabling teams to explore targeted policy scenarios with transparency and flexibility.

Ultimately, The FRIDA 2.0 Economy Module broadens the possibilities for climate-economic analysis and policy development. By capturing both short-term volatility and long-term outcomes, it serves a valuable tool for researchers, policymakers and stakeholders seeking to understand how the global economy may navigate the pressing challenges posed by climate change.

1. Introduction

FRIDA is a System Dynamics Integrated Assessment Model (IAM) modeling the complex interactions between the global socio-economic system and the global nature-climate system at a highly aggregate level (see WorldTrans Deliverable D3.5 Section 2 for an explanation of the supporting methodology). The aim of the model is not predictive, but rather the identification of high-leverage process-oriented feedback loops linking the two macro-systems over a time horizon of roughly a hundred years for the purpose of policy-development (see WorldTrans Deliverable D3.5 for documentation of the high-level feedback processes it represents).

The economic module of FRIDA has been developed *ex novo*. Its foundations have been laid in FRIDA 1.0. The 2.0 milestone marks the inclusion of the labor, innovation and central banking submodules, bringing the module to functional completion. While many expansions and refinements are possible, with some of them, regarding inequality measures and policy implementation, being planned for the immediate future, the module achieves all the intended aims detailed in the WorldTrans project proposal, and is ready for scientific evaluation and stakeholder use. In fact, publishing activities based on its outcomes have already started this year.

The report is organized as follows. Section 2 illustrates the key features of the model and the reasons behind the consortium's choices in this regard. Section 3 describes the various submodules composing the Economy Module, their mechanisms and the assumptions underlying such mechanisms. Section 4 provides a selection of key economic outcomes produced by the model and explains their most relevant and original features. Section 5 concludes.

2. A global Schumpeterian model of economic development under climate constraints

FRIDA 2.0 Economy Module can be described as a novel global Schumpeterian model of economic development under climate constraints. The Schumpeterian qualifier indicates that the model is an instance of monetary, rather than real, analysis (Schumpeter, 1954), of a disequilibrium economy. (Schumpeter, 1934), whose development is driven by innovative investments in an endogenous money context (Schumpeter, 1939). This section describes in detail the primary features of the mode in logical order and the reasons supporting their choice.

2.1. Why a new economic model?

There are several established IAMs with comparable scope to FRIDA whose economic modules might have been used as a basis for FRIDA's (Masui et al., 2011; Calvin et al., 2019; Stehfest et al., 2014; Krey et al., 2020; Fricko et al, 2020; Hilaire & Bertram, 2020; Emmerling, 2016). When planning the research project, however, the consortium decided on building an entirely new Economy Module from the ground up instead. There were several reasons supporting this costly decision. The primary one was fitness for purpose. While similar in scope, none of the existing IAMs' economic modules could simulate the processes we needed to model to reach our analytical objectives, such as the simulation of aggregate monetary and financial mechanisms, at a level of detail consistent with our aim of performing feedback loop dominance analysis. Furthermore, developing a new Economy Module would facilitate the communication of its results, as the consortium would have a complete knowledge of its mechanisms and limitations. Finally, it would help to achieve other key project goals such as the development of European modelling competence.

The original FRIDA Economy Module has a number of features making it unique among the IAM community. It is a Schumpeterian model of a global monetary economy in disequilibrium. This is quite different from the more commonly used dynamic Computable General Equilibrium models. The reasons supporting this divergence are many, stemming from the fundamental fact that a CGE model would not be an adequate methodological support for the pursuit of WorldTrans' analytical goals. Here is a breakdown of the arguments supporting the key design choices of FRIDA's Economy, presented in logical order.

2.2. Why a global model?

FRIDA is a global scope model that focuses on the two-way coupling of the climate and human systems. Our primary objective of producing an IAM of manageable complexity able to couple these systems made a global scope the default choice in this regard, due to the inherently global nature of the climate systems, despite the significant simplifications that such a choice implied. This choice introduced significant friction, however, with the representation of the human systems, central among them, the economy. While the current economic system is global in scope, following decades of increasing trade, investment and migration flows between countries (Goldin & Reinert, 2006), several key economic mechanisms take place at the national level. While their outcomes could be aggregated, the underlying causal drivers can be lost, or oversimplified, in transition. Furthermore, both monetary and fiscal policy are set at the national level, with a few significant monetary exceptions; their aggregation at the global level is one of those heroic assumptions which economists should not adopt lightly.

Consequently, one of the first key discussions held by the consortium regarded the globally aggregated nature of FRIDA. It was immediately apparent that a model focused on a single region would not be consistent with our goal of two-way coupling of the climate and human systems. A regional model would still be global in scope, yet divided. This regional division would have allowed for a number of mechanisms, natural and socio-economic, to be modelled in significantly more detail. However, it would have also entailed a multiplication of effort as not only the model would have had to be calibrated for *n* amount of regions, it would have to feature *n(n-1)* interaction dynamics, including trade, investment, monetary exchange and migration, not to mention the significant natural processing of exchange. This amount of work was deemed incompatible with the scope of the project and its resources, especially once the significant novelty involved in the design of FRIDA was taken into account. Furthermore, from the economic perspective pertaining to this report, regionalization would not solve the issue of national aggregation, thus maintaining the constraining assumptions while significantly increasing the complexity. Thus it was decided that FRIDA 1.0, 2.0 and 3.0 would retain an aggregate global scope, while reserving regionalization efforts for future research developments.

2.3. Why a disequilibrium model?

The choice to pursue a process-based, disequilibrium modelling approach, eschewing the equilibrium method and corresponding assumptions, was made possible by the use of dynamic ordinary differential equations as our modelling method of choice (Cavana et al. 2011). This is a clear advantage, in light of the significant idiosyncrasies affecting the economic analysis of climate change. First, the market instruments required to mediate climate impact are either in their infancy or simply missing in real life (Stern, 2022). Second, the significant uncertainty affecting the relevant natural processes and their consequences, the global nature of the problem and its social and distributional dimensions outline a significant set of market failures (Stern et al., 2022). Since climate-related markets are incomplete, imperfect and partially unable to produce optimal outcomes, equilibrium assumptions would have conflicted with FRIDA's goal of simulating realistic coupled socio-economic/natural feedback loops.

Second, one of the research aims of WorldTrans was to integrate the monetary and financial dimensions within a fully-coupled natural/socio-economic IAM. While the CGE framework allows for such integration (Robinson, 1991), the underlying equilibrium assumptions constrains the role of money and finance to the short-term, excluding the possibility of endogenous systemic crises with enduring consequences (see Adelman & Yeldan, 2000 for an exogenous solution). Consequently, a CGE solution would have prevented the full coupling of financial and monetary dynamics with natural dynamics and constrained *ex ante* the scope of such mechanisms. Thus, adopting a CGE approach would have prevented the exploration of these feedback loops, one of FRIDA's key analytical aims.

Third, a key aim of FRIDA is simulating the processes connecting the socio-economic and natural domains by modelling the explicit connecting mechanisms. Many of the feedback loops connecting the natural and socio-economic domains can be described from an economics perspective as operating in the short term, meaning that they would be incompatible with the long-term assumptions commonly adopted by economic modules operating on aggregate production functions. For example, extreme climate events can affect both existing economic activities and planned investments (Griffin et al., 2019). Since these short-term effects could have significant hysteresis effects, they need to be integrated in our analysis. Even if their impact would be limited to the short-term alone, they would still be relevant for policy-making purposes, as they should be accounted for in the evaluation of costs and benefits associated with specific interventions. Since one of the aims of FRIDA is to support policy-making, short-term effects should be integrated within the analysis.

A final reason supporting this choice arises from outside economics. FRIDA's physical modules are characterized by persistent imbalances. One of our analytical aims is to capture the economic consequences of such imbalances, not only in terms of their final socio-economic effects, but also including the possible pathways through which such effects are operated. In short, we aim to model coupled nature/socio-economic feedback loops as processes, albeit at an aggregate level of analysis. An economy in persistent equilibrium would have implicitly eliminated such possibility, thus again constraining the scope of our analysis.

Our disequilibrium choice greatly reduces, although it does not eliminate, our ability to identify optimal policy sets, due to the lack of utility maximization assumptions. However, considering the significant limitations of most IAMs in this regard (Ackerman et al., 2009), we believe this tradeoff to be acceptable, in light of the significant gains in terms of scope and realism described above.

2.4. Why a monetary model?

The second defining feature of the FRIDA's Economy Module is its monetary nature. As mentioned above, one of the primary aims of WorldTrans is to integrate monetary and financial mechanisms within Integrated Assessment Modelling. Since a real analysis

approach would have marginalized such mechanisms, a monetary approach was the obvious choice. Although the choice is clear in light of the aim, we still need to justify our decision to integrate monetary and financial mechanisms as a potentially significant mechanism for a model coupling natural and socio-economic feedback loops.
Firstly, there is a significant and growing body of empirical research documenting the financial impact of climate change, especially in regard to failure rates of investments, leading to increased, unexpected bankruptcies (Bartsch et al., 2024; Carattini et al., 2023; Feng et al., 2024). These unexpected defaults produce short-term negative employment shocks and drive long-term changes in lending standards, as the financial sector adapts their future growth expectations accordingly, decreasing the social costs of climate change but also negatively affecting investment and therefore both quantitative and qualitative economic development (Dell'Ariccia and Marquez, 2006; Fishman et al., 2024; Lown and Morgan, 2006; Rodano et al., 2018). The mounting evidence supporting the existence and relevance of these mechanisms has even prompted monetary authorities to reflect on how to amend and improve their financial stability policies accordingly (Brunetti et al., 2021; Giuzio et al., 2019).

These mechanisms, however, are marginalized in current IAM literature, which is still dominated by real analysis, due to its inherent long-term perspective (Pollitt & Mercure, 2018). However, we believe that the potential for climate-related financial damages to endanger macrofinancial stability, combined with the potentially significant compound impact of these damages on accumulation patterns, and consequently growth potential, are significant reasons to integrate monetary and financial dimensions within long-term focused models. As described in Section 4, these dynamics are part and parcel of the most significant climate-related feedback loop modelled by FRIDA 2.0.

The other reasons to build a monetary model of the economy relates to the primary aims of WorldTrans. The first relates to the aim of facilitating policy-making. Integrating monetary and financial aspects enable the simulation of key policy elements, such as alternative funding strategies, including e.g. monetization (Kedward et al., 2024), trade-offs, such as the inflationary pressures arising from ambitious government intervention vs the potential transformative impact of the latter (Del Negro et al., 2023) and the collaboration between government sector and the financial sector in order to mobilize the resources required by the green transition, an increasingly relevant phenomenon (Wang & Ma, 2021). Secondly, the explicit integration of monetary elements also facilitates communication between researchers and stakeholders, including policy-makers. For the latter in particular, financial considerations are paramount, decreasing the perceived relevance of models who eschew monetary considerations. This aligns with the primary aim of WorldTrans, namely transparency.

Finally, money and finance are key mediators of human behavior. WorldTrans aims to improve the integration of the human element over current IAM practices. While FRIDA 2.0 does not feature an integration of monetary and financial mechanisms with changes in social norms and human behavior, it does provide the necessary framework for this integration to be developed at a later stage by the global research community.

2.5. Why a Schumpeterian model?

The final defining characteristic of FRIDA's Economy Module is its underlying Schumpeterian theoretical framework. Nowhere is this more in evidence than in the substitution of the aggregate production function approach for a dynamic circular income flow method (Schumpeter, 1934). The reasons supporting this choice are closely connected to the discussion above. Having established that a disequilibrium, monetary economic module was needed, a Schumpeterian framework appeared as a natural choice, due to the inherently disequilibrium and monetary nature of Schumpeterian economics (Schumpeter, 1954). Furthermore, FRIDA's primary object of analysis is a system-wide process of transition, successful or otherwise, towards more sustainable development pathways brought about by mounting climate-related constraints. This is an inherently innovative process, implying qualitative, potentially disruptive change on a global scale, involving both private and public agents. Consequently, the Schumpeterian framework, focused on innovation and qualitative development, private and public, including both positive and negative consequences, is an appropriate theoretical instrument for the work at hand (Schumpeter, 1942).

Additional considerations deserve to be mentioned. First, Schumpeterian economics is less affected by political bias, due to the strong beliefs of the founder in the necessity of separating analysis and practice (Schumpeter, 1943; 1984). Consequently, it is able to portray a wide spectrum of effective policies, thus broadening the scope of potential use of FRIDA. An example of this flexibility is provided by the fact that, since Schumpeterian theory extends beyond pure market economies (Schumpeter, 1942), it is able to support the analysis of alternative institutional configurations, such as those that would be theoretically required by a post-growth scenario (Jackson, 2021). Second, Schumpeterian models are inherently fragile, being aimed towards the analysis of both physiological and pathological macroeconomic oscillations (Schumpeter, 1939). This feature is a requirement to realize our aim of evaluating the full extent of the potential role played by monetary and financial mechanisms in a climate change context. Finally, FRIDA will be the first Schumpeterian System Dynamics IAM, and the second Schumpeterian IAM in general, following the Agent-Based Dystopian Schumpeter meeting Keynes model (Lamperti et al., 2018). By contributing to foster theoretical and methodological variance in the field, we hope to contribute to its analytical growth.

Having explained the main features of the model, the next section details its submodules and the various mechanisms they contain.

3. FRIDA's Economy Module

The Economy Module is one of seven modules in FRIDA, and represents the global economy. All internal processes are simulated in nominal terms, consistent with the module's monetary framework (real GDP is calculated by adjusting for inflation in the GDP submodule, as described in Section 3.6. It receives inputs from the Climate, Land Use and Agriculture, Demographics, and Energy modules and provides outputs to the Demographics, Resources, Energy and Behavioral Change modules. A schematic representation of these interactions is provided in figure 1. While embedded in FRIDA, the Economy Module can also function independently as a stand-alone macroeconomic model of growth under exogenous environmental constraints. For explanation of the high level interactions between all the modules, and how the Economy influences the rest of the model, see WorldTrans Deliverable D3.5.

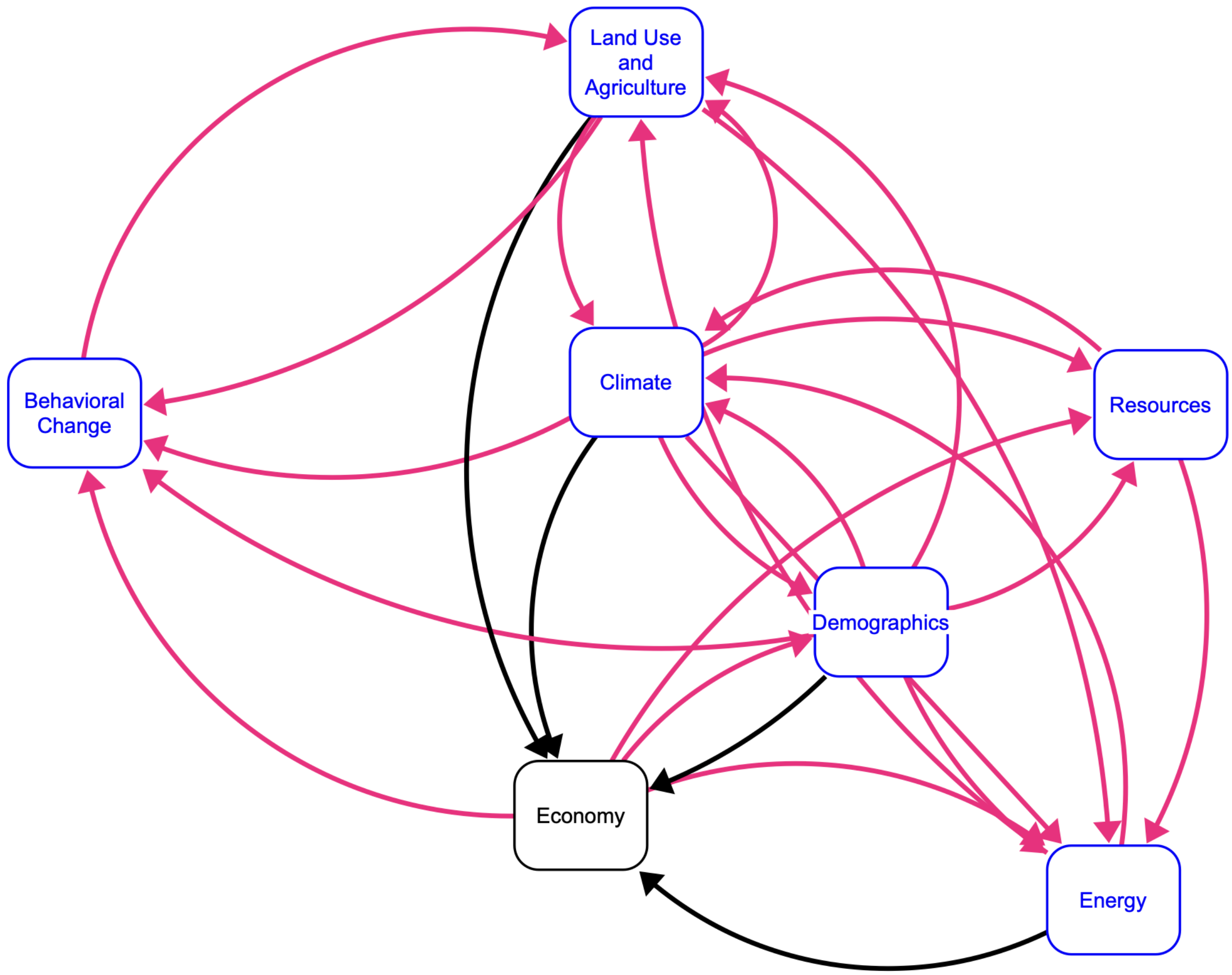


Figure 1: FRIDA's Modules. The seven high level modules comprising the FRIDA model and the connections between them. The Economy Module and its inputs from other modules are in black.

Aligning with the development goals of WorldTrans, the Economy Module's development was focused on computational efficiency and conceptual clarity. For these purposes it is highly aggregated. The module includes 514 equations, of which 33 are state variables. It replicates data sourced for the period 1980-2023, covering the key macroeconomic indicators GDP, investment, consumption, government expenditure, government debt to GDP ratio, inflation, unemployment, and wages. These time series were sourced from the World Bank, IMF, OECD, and ILO, ensuring consistency and reliability (see Norwegian Meteorological Institute (n.d.) for a complete list of data sets used in FRIDA).

The internal structure of the Economy Module consists of seven submodules, each representing distinct but highly interconnected processes as showcased in figure 2. This section documents the processes represented within each of them, and how they interact.

First, the Circular Flow submodule will be described, followed by Finance, Innovation, Government, Employment, and finally GDP and Inflation.

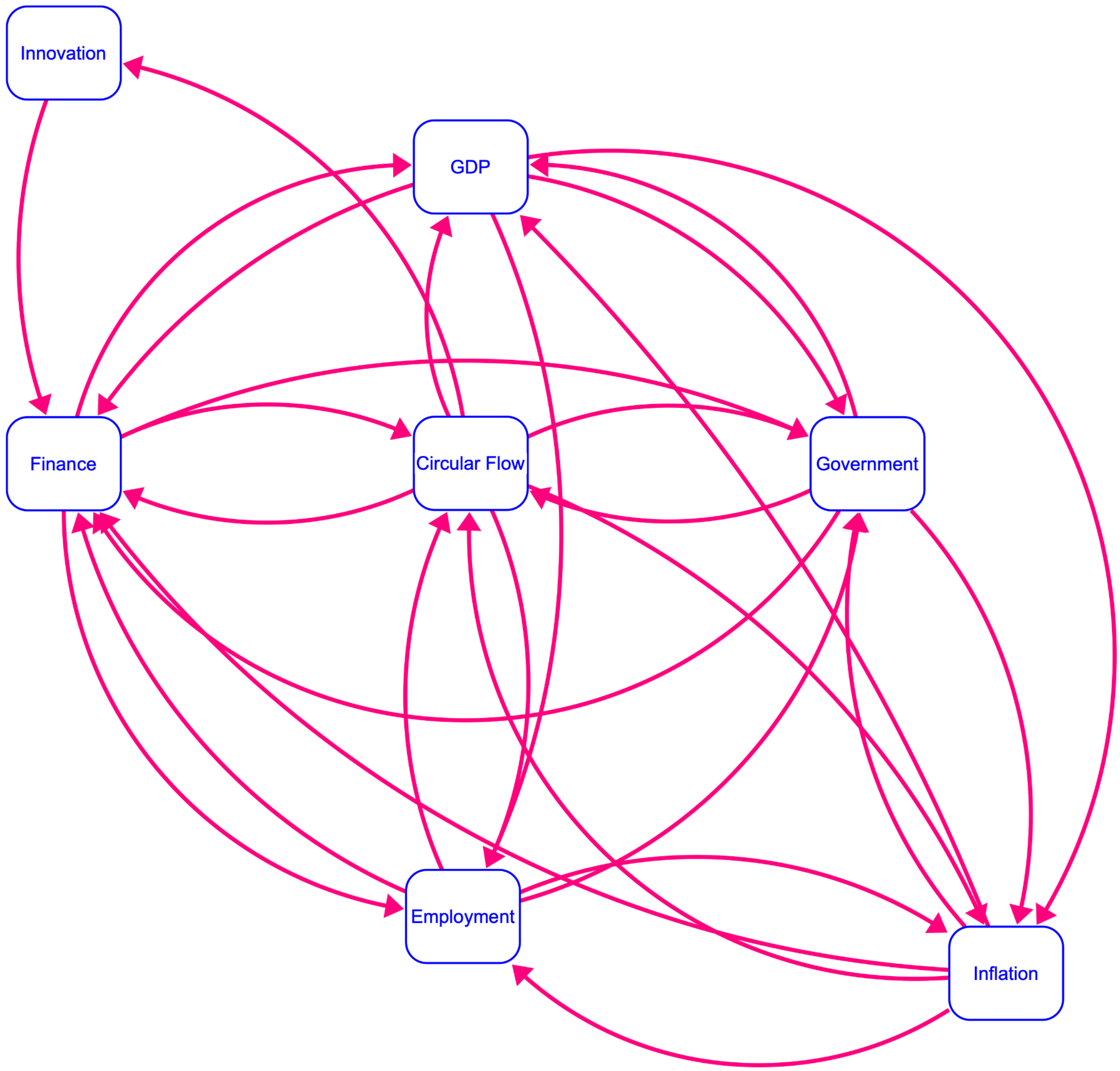


Figure 2: The Economy Module's Submodules. The seven submodules comprising the Economy Module of FRIDA, and the connections between them.

3.1. The Circular Flow

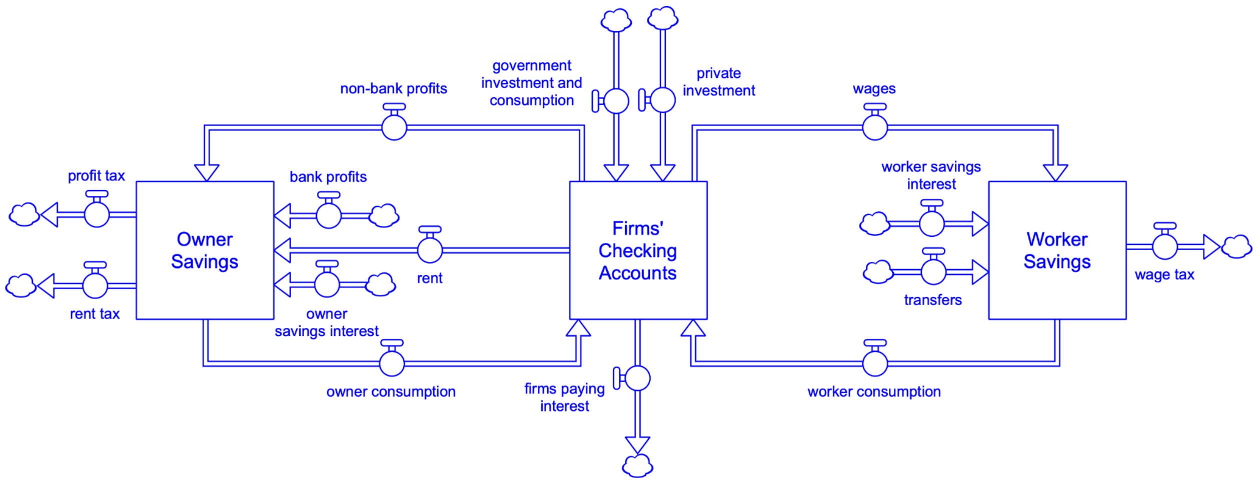


Figure 3: The Circular Flow. A stock and flow diagram of households (owners and workers) and firms, and their income flows.

The Circular Flow Submodule simulates the processes of production and consumption, representing the behavior of two aggregate agents: households and firms. The processes represented in the government, employment, and finance modules greatly affect the circular flow, but are modelled separately for conceptual clarity. While this section focuses on the income flows in and out of firms and households, the details of these flows that lie outside the Circular Flow Submodule will be covered in the sections corresponding to their respective submodules.

Households are disaggregated into workers and owners, following established practices in stock-flow consistent modelling of a monetary economy (Godley & Lavoie, 2006). Workers and owners are differentiated not along individual households or people, but instead as follows: owners own all productive factors, workers own none. Naturally, a single person can own assets while also being employed. The purpose of this disaggregation is to track the mechanisms affecting the flow and accumulation of different income streams. For both, a percentage of their respective net income is immediately spent on consumption. Owner consumption also includes additional retreating costs from SLR. The remaining income after consumption accumulates as savings which is represented by two state variables, owner- and worker savings, and conceptualised as accounts representing aggregate deposits from owner- and worker incomes, respectively.

The percentage of income spent on consumption is calculated using the same method for workers and owners, but parameterised differently under the assumption that a larger share of worker income is spent immediately, while a larger share of owner income is saved. This is because income from profit by and large tends to be allocated to long term savings goals, including retirement, while a higher portion of income from labor tends to be spent on day to day expenses (Carroll et al., 2017). The level of consumption of both groups is determined by the relationship between income and each group's dynamic savings goal. This savings goal, which represents a desired level of savings relative to income, adjusts gradually over time as each group's financial situation changes. When income rises, both groups revise their savings target upwards after a delay, reflecting a gradual reassessment of their financial security (Jappelli & Pistaferri, 2010). With a similar lag the savings goal will adjust downwards with reductions in aggregate income. The consumption decision follows a rule where 75% of each group's income, minus the shortfall between their current savings and their target savings level, is spent on consumption – with a hard floor to prevent households from having unrealistically low consumption levels under extreme conditions (Andreyeva et al., 2010). Furthermore, consumption adjusts over time to reflect gradually changing consumption habits. Not yet described is the role of inflation in increasing (nominal) consumption. Inflation has an immediate effect on both groups' consumption as prices change, net of the negative impact of additional unemployment, consumption goes up (in the absence of any other limiting factors) in an attempt to maintain the same standard of living (Burke & Ozdagli, 2023).

The consumption expenditure of each group flows into a third state variable, the firms' checking account. This variable represents all of the deposit accounts for all of the world's firms containing an aggregate store of funds available for paying out various forms of income to households. The income streams that flow from firms checking accounts to households consist of wages, which go to workers, and rent and profits, which go to owners. The process that determines what wages and rent are is modeled in the employment module, and will be discussed in Section 3.5.. Together, wages and rent reflect economic production as they represent the compensation received by households (the aggregation of owners and workers) in exchange for their contribution of productive services to the production process. These required payments are drawn from the firms' checking account. Profits consist of the residual firm income after all required payments have been made by firms. They are distributed to owners gradually over a period of approximately three years as firms require working capital to maintain operations (Larkin et al., 2017).

In addition to profits, wages, consumption and rent, there are additional income streams that don't flow out of the firms' checking account. We represent government transfers (welfare payments) as contributing to the worker subset of household income. The process for determining government transfers is modeled in the government module and discussed in Section 3.4.. The savings of both workers and owners also receive interest paid by the banks represented in the Finance Submodule (Section 3.2)., Bank profits are represented separately from the profits already discussed. Although, these profits have much the same role from the perspective of the circular flow and are counted as an owner income stream, because bank profits eventually flow through to the owners of the banks. Bank profits are not drawn from the firms' checking account, because banks are modeled separately from general firms, and this process is explained in Section 3.2.. Moreover, wages, profits and rent are taxed, creating revenue for the public sector which is used in the Government Submodule (Section 3.4.).

The circular flow, as explained thus far, cannot grow on its own. Income would circulate between firms and households, leading to a stable equilibrium as savings goals are met (Schumpeter, 1934). Growth is achieved through private investments originating in the Finance Submodule (Section 3.2.), which lend money to firms and increase the balance in their checking account. The purpose of these loans is for expanding their productive capabilities. Firms pay interest on these loans depending on the risk level as determined in the finance module (Section 3.2.). A second potential source of growth in the circular flow are governments, who also make investments, and spend on consumption, with both flows going into the firms' checking account; when government expenditures exceed tax revenues, they increase general income, although the increase may be purely nominal depending on productivity growth and employment trends. These government expenditures are determined in the Government Submodule (Section 3.4.). The next section describes the Finance module and how it mediates private investment and enables growth.

3.2. Finance

The Finance Submodule simulates the global financial system by capturing the mechanisms governing private investment, credit creation, and financial stability through an aggregate representation of the banking sector. The module represents the processes of: asset creation, banking, and investment through lending. It also includes processes which model the amount of resources dedicated to exploratory investments, as well as capturing human behavior around managing banking and investment-related risks. The following sections explain the mechanisms and processes contained in the Finance Submodule in detail.

3.2.1 Investment, Lending and Loan Classification

This subsection describes the decision-making mechanisms behind bank lending, the classification of loans, and risk factors. Key concepts include loans, which are classified as bad, good, safe or exploratory, lending standards, which represent the banks predilection for giving out money, and defaults, which arise from the eventual failure to repay (bad) loans. Loan volume is modeled by capturing the banks decision making processes regarding loan origination. The banks are modeled as wanting to return the maximum profit to their owners, which means on the one hand they want to create as many (profitable) loans as possible, but on the other, they don't want to give loans to those who will not repay them. Therefore banks must carefully balance their own internal lending standards (which tracks the bank's perceptions of people's ability to repay) with their desire for expanding their asset base. The banks' desire to expand their asset base is modeled as a long term historical reference of the past rate of growth in loan volume (Rodano et al., 2018).

To gauge the expected profitability of lending, we have represented a process by which banks observe the current GDP growth rate relative to their preconceived expectations for what GDP growth should be. Those expectations are generated by taking the average growth rate over the past two and a half years (Albertazzi & Gambacorta, 2009). The banks predilection to lend, i.e. their lending standards, are represented as a relative index, adjusted over time in response to the default rate and past lending standards (Fishman et al., 2024). If the rate of loan creation exceeds the economy's growth potential, loan quality deteriorates, leading to increased defaults (Kraft & Jankov, 2005). As the rate of defaults relative to the size of the loan portfolio increases, lending growth decreases, and vice versa (Gjeçi et al., 2023).

We represent the assets of the banks in three main state variables: risky loans (the summation of bad loans and good loans), as well as safe loans. In the model we classify new loans as either "good" or "bad" at issuance and accumulate them into distinct state variables. Due to information asymmetry, we represent the reality that banks consider both good and bad loans as risky. Because the banks consider all new lending as risky, we represent a process by which banks apply a risk premium to these newly originated loans (Liao et al., 2009). In our model, as these risky loans (good and bad) mature, bad loans are revealed to be non-performing as they default. Once defaulted, they are removed from the bad loans state variable and effectively written off as losses for the bank. Good loans, on the other hand, as they are revealed to be performing, are reclassified as safe assets for the bank and flow from good loans to safe loans – the third class of loans, and another state variable. Once a loan has been demonstrated to be safe, a risk premium is no longer applied. Interest rate dynamics can modify the classification of loans (Adrian & Shin, 2008), as liquidity constraints beget insolvency, and abundant liquidity enable less profitable investments to survive, as described in detail in the next subsection.

The proportion of new loans classified as bad at origination is determined by the "failure rate". The failure rate has a baseline of approximately 3.5%, reflecting normal liquidity conditions with well-functioning financial markets, and is dynamically adjusted based on economic and climatic conditions (World Bank, n.d.): It depends on lending standards, the difference between investment growth and GDP growth, and the surface temperature anomaly (STA) which is determined in the Climate module (Beck et al., 2015; Carattini et al., 2023; Feng et al., 2024). Higher lending standards lead to stricter screening of investment opportunities, reducing the failure rate as banks allocate credit more selectively (Van der Veer & Hoeberichts, 2016). Conversely, looser lending standards increase the failure rate as riskier investments are pursued. Additionally, when the growth rate of annual investment volume exceeds GDP growth the failure rate also increases. This occurs because investment expands faster than the economy is able to generate profitable investment opportunities (Kraft & Jankov, 2005). The STA further increases risk: as global temperatures increase above pre-industrial levels, extreme weather events increase the probability of new investments failing (Carattini et al., 2023; Feng et al., 2024).

The final class of loans, represented by a state variable, are "exploratory", standing for funding of innovative projects. These loans contribute to productivity growth, calculated in the Employment Submodule. Banks engage in exploratory lending when seeking new investment opportunities, particularly in periods of high investment activity relative to growth potential (Mendi, 2024). When the growth rate of nominal investment exceeds real GDP growth it puts upward pressure on exploratory lending (Nanda & Rhodes-Kropf, 2013). This reflects situations where credit expansion is not matched by real economic output growth, prompting banks to fund innovative ventures that might open new avenues for additional profit. Conversely, a decline in the growth rate of annual bank profits places a downward pressure on exploration, as banks become less willing to take on more risk (Ahmad, 2021). Thus, exploratory loans fluctuate based on financial and macroeconomic conditions.

3.2.2 Interest rates and Other Sources of Loan failure

This subsection explains in detail how interest rates are set, how they affect loan failure, and every other mechanism by which loans can fail. While all bad loans eventually default – except for those that may be reclassified as good as a result of improved liquidity conditions – all other classes of loans (good, safe, and exploratory) can also fail under specific conditions. Interest rate hikes can cause failures across every loan class (Adrian & Shin, 2008). Safe loans can also fail due to SLR and R&D-driven innovation. Lastly, exploratory loans can be made vulnerable and fail from GDP deceleration.

Our economic model includes the representation of central bank actions. That central bank sets a policy rate through a process represented in the Government Submodule (Section 3.4.). On the basis of the policy rate, the private-sector average safe interest rate is derived as a moving three year average of the policy rate. The average private sector risky interest is set above the safe rate, by adding a risk premium to it. This premium changes dynamically to reflect the banks' perceived risk profile, which is proxied by the default rate relative to the total number of risky loans. As defaults increase, the risk premium rises, making new risky loans more expensive (Gjeçi et al., 2023). Conversely, lower default rates reduce the risk premium, easing borrowing conditions (Fishman et al., 2024).

Sudden changes in interest rates directly impact loan performance. Interest rate cuts can move a share of bad loans into good loans by alleviating liquidity constraints, allowing loans that would otherwise default to remain viable (Bhandari & Weiss, 1993; Minsky, 2008). Interest hikes, on the other hand, increase debt servicing costs and can lead to failures across all loan classes, including safe loans, as they become too expensive to sustain (Adrian & Shin, 2008).

In addition to interest hikes, safe loans can also fail from SLR. Higher sea levels increase the severity of floods, creating losses and damages in coastal areas in the absence of adaptation. Safe loans are also subject to failure from R&D-driven innovation, which renders a portion of existing investments obsolete (Diamond, 2006; Schumpeter, 1934, 1942). The value of the total safe loans issued by firms reflect the value of their productive assets. A portion of these assets is allocated to exploratory uses (R&D). The extent to which firms allocate these assets to R&D depends on their innovation orientation, which is determined in the Innovation Submodule (Section 3.3.). While R&D activities improve economy-wide productivity – as determined in the Employment Submodule (Section 3.4.) – the obsolescence it creates causes a share of safe loans to fail over an average of 10 years as new technologies diffuse and gradually displace previous techniques (Chinloy et al., 2010)

Lastly, while exploratory loans can also fail from interest hikes, they mainly fail due to GDP deceleration. This reflects the effect of economic slowdown on the viability of the highest risk investments going to innovative ventures (Sedláček, & Sterk, 2017). As GDP decelerates, it reduces expectations of return on investment, making these loans more prone to fail due to liquidity constraints as resources are redeployed to less risky projects.

3.2.3 Bank Profits, Solvency, and Government Intervention

Households' accumulation of savings and the banking sector's profit incentive drives issuance of loans, as banks attempt to generate enough returns to remunerate deposits and distribute profits, a monetary rendition of the savings/investments nexus (Bernanke & Blinder, 1988). The issuance of loans expands both sides of the banking sector's balance sheet: when banks extend credit, it increases their assets in the form of loans, and creates new liabilities in the form of additional deposits held by firms (McLeay et al., 2014). This mechanism injects new money into firms, from where it circulates between households' and firms' deposit accounts. The difference between accumulated loans in the Finance module and the accumulated deposits in the Circular Flow constitutes the banks' equity.

The amount of profits distributed by banks is a fraction of the total equity, dynamically adjusted based on the annual growth rate of the equity. Declining equity puts downward pressure on bank profits, and vice versa (Menicucci, & Paolucci, 2016). The bank profits flow into the circular flow as an income stream. If the bank asset-to-liability ratio falls below 1.02, we represent a process in which the government intervenes and provides solvency support, subsidising the banking sector to ensure financial stability (Gup, 2003).

3.3. Innovation

The Innovation Submodule simulates private firms' orientation toward innovation based on economic conditions. While the banking system also contributes to innovation through exploratory lending, this process is determined in the Finance Submodule as described in Section 3.2.1. Following our Schumpeterian approach, we identify innovative investments from both incumbents and new entrants as a primary driver of long-term economic growth (Wong et al., 2005). Specifically, the submodule governs the amount of private assets employed as part of R&D and other exploratory activities, with implications for defaults in the Finance Submodule, and productivity growth in the Employment Submodule – reflecting creative destruction (Schumpeter, 1942).

These innovative investments fluctuate across the business cycle, increasing/decreasing as a reaction to low/high profit rates (López-García et al., 2013; Mendi, 2024). The firms' orientation towards innovation is represented as an index initialized at one. When the growth in the firms' cash reserves slows down, firms rapidly become more inclined to innovate, reflecting an increased urgency to explore new potential revenue streams. Conversely, as cash reserves grow, this orientation declines gradually, indicating a preference for stability and risk aversion over uncertain R&D investments.

3.4. Government

The Government Submodule simulates fiscal and monetary policy, modelling governments and central banks as aggregate agents responsible for managing tax revenue allocation, government debt dynamics, and the policy rate. Tax revenues collected from households are redistributed through public investment, consumption, and transfers, with total government expenditure levels adjusted in response to GDP and the ratio of expenditures to GDP. Additionally, the composition of the expenditure is influenced by STA, shifting expenditures from transfers to consumption as it becomes necessary to spend continuously to repair and maintain infrastructure impacted by climate change (Qiao et al., 2015). The central bank sets the policy rate based on the current inflation- and unemployment rate to manage them (Schooner & Taylor, 2009). This section describes these mechanisms in detail.

3.4.1. Government Revenue, Expenditure, and Debt

Government expenditure, excluding interest payments on outstanding debt, is determined as a percentage of total tax income, which is levied on the flows of wages, profits, and rents (Narayan, & Narayan, 2006; Ram, 1988). The percentage of tax income spent dynamically adjusts based on the governments' fiscal stance, measured by the debt-to-GDP ratio. This ratio imposes constraints on the government's expenditure relative to its tax-derived income: when the ratio is below 1, spending can reach up to 130% of tax revenue. However, as the ratio rises above 1, expenditure will gradually decline to a minimum of 90% as debt-to-GDP ratio reaches 2 (Ewing et al., 2006). Therefore, while the BAU scenario of FRIDA 2.0 features continuous government deficits, alternative scenarios could allow for government surplus.

A key mechanism that we represent, which underlies the government's ability to spend is borrowing and consequent government debt. As previously mentioned, the government is able to spend above their (tax-based) income when the debt-to-GDP ratio is below one. This means our model simulates a deficit which we model as the issuance of debt from the government sector to the banking sector (Fang et al., 2022). It is important to note that our model does not include non-bank holdings of government debt, because our model lacks aggregated wealth portfolio management dynamics. We model the government deficit as the difference between total government expenditures and total tax revenues. Government expenditures are modeled as the sum of investment, consumption, interest payments and transfer payments. In addition to deficits created via these regular spending and taxation processes, we model a second process for creating government debt, which is that additional government debt can be directly issued (circumventing being added to the circular flow) to stabilize the financial system should the banks be insolvent, effectively "bailing them out".

Key to the evolution of government expenditures are the dynamics which drive changes in the government's interest rate. The interest rate on government debt is derived from the policy rate averaged over seven years, reflecting the composite nature of government debt duration (Dembiermont et al., 2015). When the debt-to-GDP ratio is at or below one, this rate aligns with the policy rate. When the ratio exceeds one, government debt is perceived to be riskier and additional interest is charged in proportion to how much the ratio surpasses one (Ardagna et al., 2007; Jacobs et al., 2020). Interest is assumed to always be paid, regardless of fiscal constraints. While this assumption ignores the empirical reality of defaulting sovereigns (Beers & Mavalwalla, 2017), the implementation of the latter is incompatible with the globally aggregate nature of the model.

As discussed above, government expenditure, after accounting for interest payments, is allocated across investment, consumption, and transfers. Approximately 5% of total expenditure is directed towards investment, while the remainder is split between consumption and transfers (Gethin, 2024). In the absence of climate related pressures, 67% of this remainder is directed towards consumption, and 33% towards transfers (ibid.). This allocation is dynamically adjusted in response to increases in STA; as climate-related losses and damages mount, consumption becomes a larger share of total expenditures to accommodate increased climate-driven repairs and maintenance (Qiao et al., 2024). Further improvements to government spending behavior, including endogenization of transfers, are planned for FRIDA 3.0.

3.4.2. Central Banking and the Policy Rate

The central banks are modelled as a single, aggregate agent, and are tasked with keeping inflation and unemployment near respective targets. Specifically, they aim for 2% inflation and 5% unemployment (Solow & Taylor, 1998). When inflation exceeds 2%, the policy rate is pushed upward to slow growth in the price level, whereas inflation below 2% will push the rate down to stimulate investment. Unemployment follows the same logic, but in reverse: if unemployment falls below 5% it will push the rate up to mitigate excessive wage growth, while unemployment above 5% will push the rate down to stimulate labour demand. These adjustments to the policy rate occur gradually, with greater weight given to inflation than unemployment (Cukierman & Lippi, 1999).

3.5. Employment

The Employment Submodule simulates how the global working-age population transitions between non-active, unemployed, and employed, and how wage rates respond to changing labour market conditions. Also included within this submodule is our representation of labour productivity. Dynamics in this submodule are driven off of public and private investment flows – originating in the Government (Section 3.4) and Finance (Section 3.2) submodules, respectively, as well as inflation, from the Inflation Submodule (Section 3.6.). Crucially, this submodule integrates productivity gains related to “creative destruction”, where innovation from the Finance and Innovation submodules (Section 3.2. and 3.3., respectively) render existing processes obsolete, but boost economy-wide productivity. Finally, rising STA counteracts productivity gains, reflecting the disruptive effects of climate change on economic activity (Dasgupta et al., 2021). This section details how these forces – labour supply and demand, wage formation, innovation and productivity, as well as climate vulnerabilities – together shape global employment outcomes in the model.

3.5.1. Labour and the wage rate

The working age population, as represented in the Employment Submodule, consists of people between the ages of 15 and 65. People aging in or out, or dying is modeled in the demographics module. The working-age population is divided into three state variables: non-active, unemployed, and employed. The non-active represents those of working age who cannot, or will not, seek work. Historically, approximately 35% of the working-age population has been in this category (ILO, 2024). Thus, the model ensures this portion of the working-age population remains in this category. The unemployed and the employed make up the labour force, and movement between them depends on the labour demand and wage dynamics.

Firms' labour demand stems from public and private investment, as determined in the Government and Finance Submodules, respectively, approximated at 20% of total investment divided by the average wage rate (ILO, 2024). The time required to hire new employees depends on the unemployment rate; as it declines, it becomes increasingly difficult to match vacancies with qualified workers (Mortensen & Nagypal, 2007).

The average wage rate responds asymmetrically to changes in the ratio of labour supply to labour demand: if the ratio falls below one, wages rise, whereas if it rises above one, wages decline at a lower rate, reflecting the relative "stickiness" of wages (Ehrlich & Montes, 2024; Grisby et al., 2021). Additionally, if inflation (as determined in the inflation Submodule) outpaces nominal wage growth, the resulting purchasing power loss can exert upward pressure on wages (Kahn, 1984). However, firms adjust wages with a lag to reflect real-world negotiation delays and the impact of existing contracts (Grisby et al., 2021).

Firing, on the other hand, moves workers from the employed to the unemployed category. Firing occurs for three reasons. First, from defaults in the finance module, which lead to layoffs proportional to the defaulted amount relative to the cost of labour. Second, from missed profits dropping below a threshold tied to the average rate of interest on private debt. The missed profits prompts firms to compensate by reducing their payroll (Couke et al., 2007). Third, from productivity growth replacing labour over time. Half of the productivity growth is assumed to translate into a proportional firing rate, achieved through layoffs spread out over an average of five years. The delay reflects the time it takes for new technologies and techniques to diffuse, and for it to displace workers (Feldmann, 2013).

3.5.2. Productivity and Climate Effects

Productivity growth in the model arises from innovative activities financed by exploratory loans (determined in the Finance Submodule Section 3.4.) and firm R&D (determined in the Innovation Submodule Section 3.3.) (Hasan, & Tucci, 2010; Kortum & Lerner, 1998). The value of both exploratory loans, and safe loans failing due to innovation are expressed as shares of GDP to enable direct comparison. Based on these normalised values, productivity growth is calculated, weighting the contribution of exploratory loans more heavily to reflect their higher transformational potential (Acemoglu & Cao, 2015). Realised productivity from these investments take on average five years to materialise, reflecting the time required for innovation to diffuse and yield economic benefits (Meade & Islam, 2006).

Lastly, labour productivity is affected by climate effects. As STA increases, labour effectiveness declines in proportion to the vulnerability of the three main economic sectors: agriculture, industry and services (Dasgupta et al., 2021). The global distribution of labour amongst these sectors is a function of GDP, reflecting the transition from agriculture to industry and services observed with higher economic output (Alvarez-Cuadrado & Poschke, 2011). Agriculture is the most susceptible to extreme weather events and higher temperatures, followed by industry, while services experience relatively milder impacts.

3.6. GDP and Inflation

GDP in this model is calculated in its own submodule using a nominal expenditure approach, summing the final purchase price of public and private consumption and investment. Due to the global nature of the model, international trade cancels out and is therefore not included. Private and public investments originate in the Finance and Government Submodule, respectively (Section 3.2., 4.4.). Private and public consumption originate in the Circular Flow (Section 3.1.) and Government (Section 3.4.) submodules, respectively. To derive real GDP in constant 2021 dollars, the model applies an inflation index calculated in the Inflation Submodule described in detail below, ensuring comparability over simulation runs.

Inflation is calculated in its own submodule, based on two components: income growth, and input-shock (Auer et al., 2019; Deniz et al., 2016; Lim & Sek, 2015). Both components can be positive or negative, but inflationary pressures have an outsized effect compared to deflationary pressures, reflecting stickiness in price levels (Altonji, & Devereux, 1999). Income growth leads to inflation when the combination of private income (from the Circular Flow Submodule Section 3.1.) and annual government deficit spending (from the Government Submodule Section 3.4.) grows faster than economic expansion potential, proxied by productivity and employment growth, referring to qualitative development and quantitative growth, respectively (Hasan, & Tucci, 2010)). This imbalance places upward pressure on the price level. The input-shock components of inflation originate outside the core Economy Module – specifically from the Energy and Land Use and Agriculture modules. When demand exceeds supply in animal products and crops, it adds to inflation. The opposite is deflationary. Other pressures arise from the growth rates in fertilizer use, crop land, grazing land, and the marginal cost of energy. Changes in these growth rates exacerbate scarcity, driving up input costs and triggering cost-push inflation. Furthermore, they proxy all historical input-shock inflation, and their inflationary contribution is weighted accordingly, capturing the impact of scarcity on real growth (Parker, 2017).

4. Model Outcomes

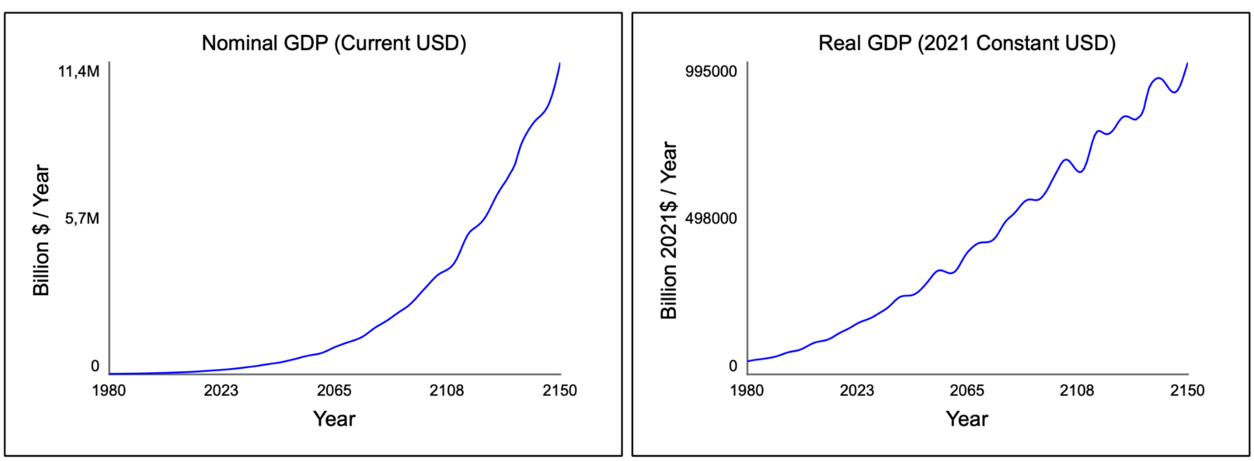
This section illustrates the key outputs, and how they are produced by the Economy Module of FRIDA 2.0, building on the Schumpeterian, monetary, and disequilibrium principles described in Section 2. In keeping with the model's non-predictive aim, our focus is on how endogenous feedback processes shape macroeconomic indicators over a century-long horizon. By highlighting the oscillatory, cyclical patterns that emerge from the model structure – without exogenous forcing – we capture the dynamic interplay among investment, innovation, credit, and government policy in a global, aggregate setting. Rather than exhaustively cataloguing all outputs, we concentrate on a handful of representative variables, covering GDP, inflation, credit, employment, and government policy. By linking these outputs to the underlying model structure, we illustrate how and why our results are obtained.

Figure 4 shows the trajectories of nominal and real GDP from 1980 to 2150. Both grow at a near-exponential rate, but also exhibit oscillations throughout the simulation time horizon. Real GDP is more volatile than nominal GDP, reflecting periods of high inflation. At a high level, credit provision by the banking sector to both private and public sector is the primary driver of GDP growth, as lending expansion stimulates investment, consumption, and government spending, thereby facilitating productive expansion.

The oscillations reflect the credit cycle at work. During upswings, relaxed lending standards allow for the extension of credit, which stimulates the growth of investment, and therefore additional money to flow into the economy which reinforces growth. Overextension, however, leads to rising non-performing loans and defaults, prompting tighter lending standards. The heightened perception of risk from defaults also triggers interest hikes, which in turn exacerbates defaults due to the mechanisms described above, leading to yet tighter lending standards, less investment, and a cooling down of the economy (Minsky, 2008).

The credit cycle has deep implications for employment. As investment grows, firms hire more workers. The resulting reduction in unemployment places upward pressure on wages via competition for labour. With lower unemployment, and higher wages, consumption grows, reinforcing growth that can lead to over-lending by banks and thus an uptick in defaults. The banks' reaction to more defaults is to, among other actions, hike up interest rates that trigger layoffs and pushes unemployment up again. Thus, the unemployment- and wage rate swings with, and reinforces, the credit cycle, as can been seen in figure 4.

This inherent instability of credit provisioning also ripples across household consumption and public sector spending, as it impacts private income and, consequently, the tax base: fluctuations in investment feed back into household budgets–albeit with delays, as consumption and saving habits gradually adjust to the influx of funds. Meanwhile, government expenditure, which is tied to taxable income and adjusted for debt levels relative to GDP, adds another layer of feedback. Crucially, the boom-bust cycles displayed in figure 4 arise from the systemic interplay of these feedback mechanisms – expanding and contracting credit, unemployment, changing investment flows and consumption patterns, and government expenditure.



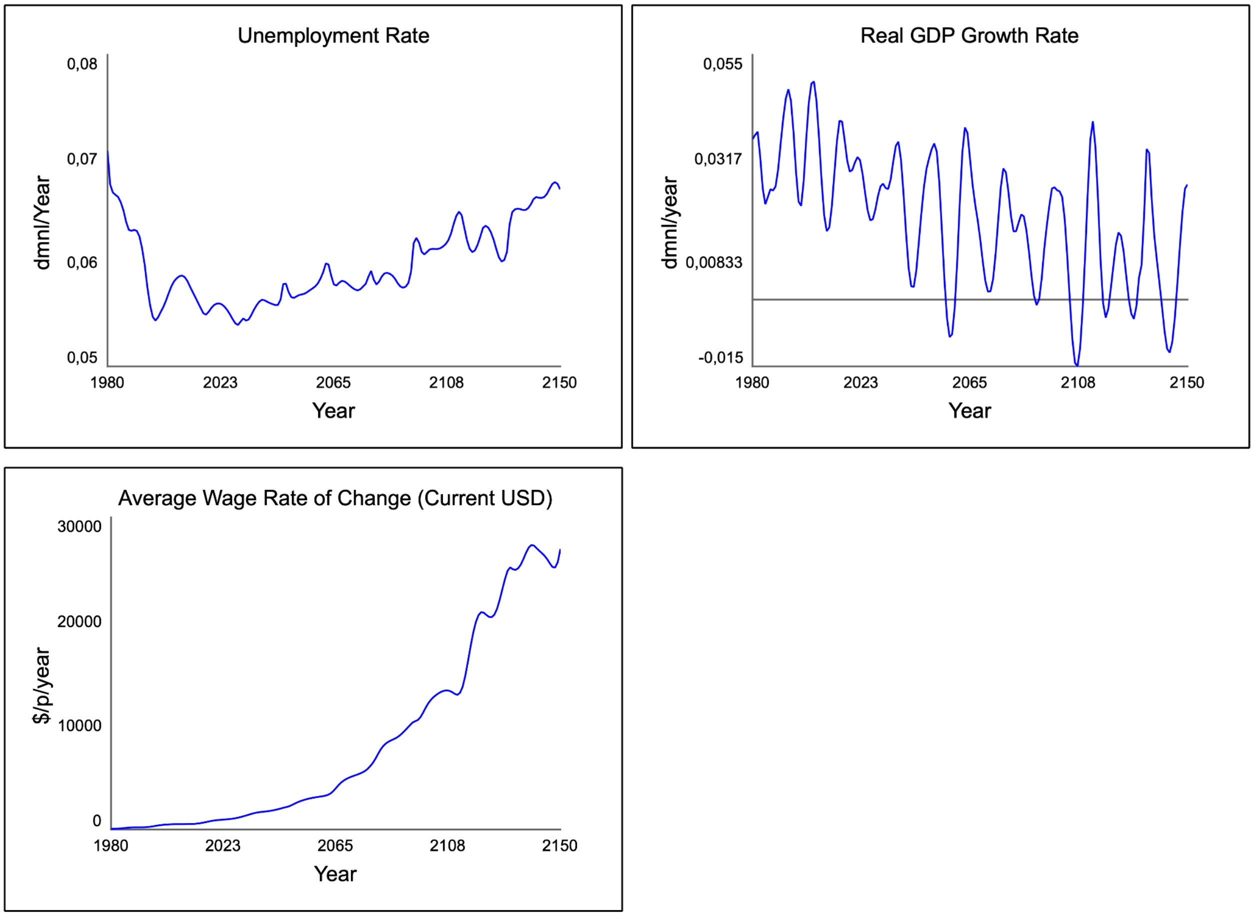


Figure 4: Key Economic Outputs. Nominal and real global GSP (top left and top right) exhibit near-exponential growth with cyclical fluctuations driven by endogenous financial and economic dynamics. The unemployment rate (middle left) also follows a cyclical pattern, reflecting total investments, bankruptcies, and productivity growth. The real GDP growth rate sees (middle right) sees pronounced booms and busts. The average wage rate of change (bottom left) trends upward over time, influenced by labour market conditions, and inflation.

Figure 5 illustrates the inflation rate, central bank policy rate, and annual productivity growth over the simulation time-horizon. Inflation oscillates around two percent in tandem with credit expansions and contractions: whenever nominal income outpaces real economic capacity proxied by employment and productivity growth, price levels grow. Conversely, when demand cools, inflationary pressures subside. The policy rate, set by the central bank, closely follows the inflation rate, being adjusted upward to temper price growth, and downward when inflation goes below an inflation target of two percent.

Productivity growth also exhibits oscillatory behavior, but for reasons unique to exploratory lending and corporate R&D. Banks invest in uncertain, innovative ventures when conventional investments are saturated, whereas firms increase their R&D when cash flow slows, seeking new avenues for profit. Both channels increase economic volatility: exploratory lending increases demand, innovation increases productivity, and creative destruction triggers additional defaults by making older techniques obsolete. Taken together, these interlinked feedback highlight the disequilibrium nature of the Economy Module, wherein the interplay of demand, innovation, and financial fragility (Minsky, 2008) shapes the price developments and the economy's long-term productive capacity.

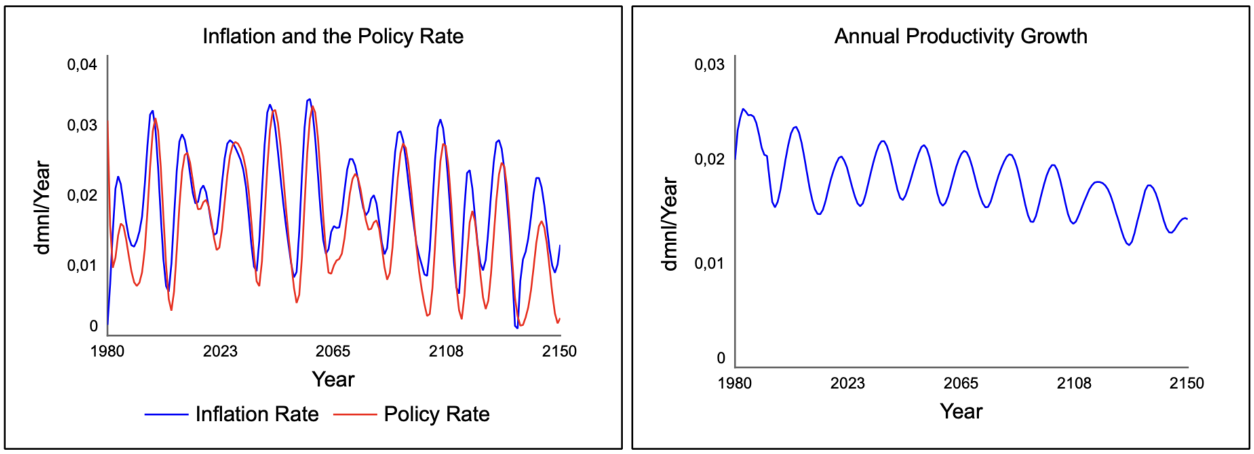


Figure 5: Inflation, the Policy Rate and Productivity. The inflation rate, influenced by income growth and the economy's productive capacity, oscillates over the simulation with the policy rate trailing it (left). The productivity growth oscillates too, dependent on innovative investments from private firms, including banks (right).

5. Conclusion

The development of the Economy Module of FRIDA 2.0 marks a significant milestone in advancing the integration of socio-economic and natural systems as specified in the WorldTrans proposal. Built upon Schumpeterian, disequilibrium-based, and monetary foundation, the module enables the simulation of short-term cycles, and their long-term economic consequences within climate constraints, as well as comprehensive policy analysis. Beyond FRIDA 1.0, the latest additions include fully endogenous submodules for employment, innovation, and central banking. These additions make for a more realistic depiction of the global economy while also allowing stakeholders to experiment with a wide set of policies for shaping macroeconomic trajectories over the century-long simulation horizon.

A key achievement of the module is its capacity to endogenously generate oscillatory patterns in macroeconomic indicators such as GDP, inflation, employment, and productivity growth. These cycles are emergent from feedback processes involving credit provisioning, production and consumption, employment and wages, monetary and fiscal policy. The credit cycle, for instance, drives booms and busts as relaxed lending standards stimulate investment until defaults trigger credit tightening, slowing the economy.

Crucially, these oscillatory mechanisms have implications for climate-related policy-making, uniquely captured by FRIDA 2.0: financial instability, investment failures, and short-term disruptions caused by the volatility have lasting, compounding effects on the growth potential and the accumulation of productive capacity. The mechanisms responsible for the volatility also allows experimentation with policy interventions unavailable to other IAMs, including central bank inflation and unemployment targets, fiscal measures, and alternate funding strategies for the green transition. These capabilities enhance the relevance of the FRIDA model for policymakers.

Looking ahead, FRIDA is poised for further developments for 3.0, and beyond. The 2.0 milestone marks the completion of the foundations for the economic module as originally envisioned. With this structure in place we can now focus on: integrating inequality measures from the Sustainable Development Goals suite of indicators, expanding the available options for policy funding, integrating central bank monetization, expanding taxation options, and endogenising aspects of the government sector to capture demographic shifts.

FRIDA's Economy Module has successfully introduced monetary and financial mechanisms to the integrated assessment modelling community. Ultimately, the Schumpeterian, disequilibrium-based approach taken with FRIDA's Economy Module broadens the possibilities for socio-economic and climate related analysis and policy development. It provides stakeholders and researchers alike with a nuanced tool for understanding how the global economy might navigate, or be shaped by, the pressing realities of climate change.

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