Disaster Risk Reduction Investment Profile Cost-benefit Analysis of Public Investment for Vulnerability Reduction in Terms of Future GDP Growth

Technical Framework and Methodology Report

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Technical Report

1. Background

The analysis of cost and benefit regarding Disaster Risk Management (DRM) policy interventions[1] is more important than ever as IDB countries face significant impacts due to increasing climate and disaster risks. Latin America and the Caribbean is considered the second most exposed region to disasters globally with over 152 million people affected by some 1,200 disaster events triggered by hazards such as floods, droughts, earthquakes, hurricanes, and volcanic activities over the past 20 years (UNOCHA 2020).

In light of these trends, the IDB has developed a comprehensive approach to disaster risk management incorporating technical and financial assistance across areas including:

(i) Risk Identification;
(ii) Prevention and Mitigation;
(iii) Preparedness, Response and Recovery; and
(iv) Financial Risk Management.[2]

International good practice shows that proactive DRM policy interventions on average yield multiple benefits that far outweigh the cost of investment (Tanner et al., 2015; MMC, 2005; Mechler, 2005; Moench et.al., 2007). Yet, the evaluation of country-specific DRM policy effectiveness requires an additional examination of place- and context-specific drivers of risk (hazard, exposure, and vulnerability) along with prospects of baseline socioeconomic development.

As trends and drivers of risks including the availability of public and private capital (and their allocation) are inextricably linked to a country´s development trajectory, a new and integrative analytical tool is needed that may shed light on policy questions such as:

- *How much public investment is needed to achieve a given level of disaster risk reduction against a specified level of hazard risk exposure?*
- *What is an optimal public resource allocation between DRM policy instruments and other productive investments that balances the need for national development and resilience building?*
- *What is an optimal mix of public resource allocation between disaster risk reduction investment and risk retention/transfer instruments?*

These policy questions are particularly relevant as IDB member countries strive to achieve interrelated goals of disaster risk management, climate change actions and sustainable development, as outlined in international frameworks such as the Sendai Framework for Disaster Risk Reduction 2015-2030, the Paris Agreement under the United Nations Framework Convention on Climate Change, and the Sustainable Development Goals. They

[1] In this technical report, DRM policy interventions include both Disaster Risk Reduction (DRR) investment (i.e. structural and non-structural interventions aimed at reducing the impact of hazards) and disaster risk financing instruments including risk retention and transfer mechanisms.
[2] https://www.iadb.org/en/naturaldisasters

also assume that national governments proactively and consciously make development planning and implementation decisions regarding disaster risk reduction. However, in many Latin American and Caribbean (LAC) countries, decision-making power resides primarily within the Ministries of Finance.

Under the IDB Technical Cooperation Project RG-T2434: Development of Public Investment Profile in Disaster Risk Reduction (https://www.iadb.org/en/project/RG-T2434), a general analytical framework and basic methods were developed and tested in select countries at the national level (Bolivia, Honduras, and Peru) and one at the local level (Rio Rocha river basin in Bolivia). While the Phase 1 methodology primary focused on the evaluation of disaster risk management policy effectiveness in terms of direct benefit (i.e., reduction in direct damage due to mitigation and risk retention/transfer instruments), a more integrated analysis is needed to take better account of:

- *Potential feedbacks between disaster risk/damage and economic activities (e.g. benefits in terms of reduction in indirect losses);*
- *Potential feedbacks between public sector disaster risk reduction investment and private sector savings and investment behavior of key actors;*
- *Potential feedbacks between public sector disaster risk reduction investment with multiple co-benefits and a country´s development trajectories.*

The above feedbacks are increasingly referred to as the ´triple dividends´ [3] of DRM investment and analyzing these interactions requires a new analytical tool that goes beyond the Phase 1 Investment Profile Model. This technical report hence describes the state-of-the-art dynamic macroeconomic modeling known as the Dynamic Model of Multi-hazard Mitigation Co-benefits (DYNAMMICs) incorporating both the concept of multiple benefits as well as risk layering (Ishiwata and Yokomatsu, 2018). The subsequent sections are organized as follows: Section 2 describes the current investment profile and the methodological improvements introduced by the DYNAMMICs framework; Section 3 provides an overview of the model setup and its theoretical foundation; and Section 4 lays out the model and its equations in detail.

2. Bank Investment Profile Methodology and its application

2.1. Review of the existing Bank Investment Profile Methodology

The Investment Profile (IP) for Disaster Risk Reduction (hereafter referred to as the Investment Profile) presented a methodology to evaluate the efficiency of alternative disaster risk management strategies that combine various policy options using the notion of risk layering (IDB, 2021). These options include investment in risk mitigation measures, namely structural/non-structural measures such as new protective infrastructures and structural retrofitting for existing vulnerable infrastructures[4], as well as financial instruments. Financial instruments include the design of a reserve fund to cope with the immediate needs for

[3] Economic Triple Dividends of DRM investment are a concept well described in and originating from Tanner et.al. (2015)

[4] It is important to note that LAC countries' budget systems (economic codes) do not always easily allow for the distillation of this information systematically (i.e., risk mitigation expenditure). DRR investments are often coded as capital works in public budget estimates.

emergency attention, restoration of basic services, reconstruction and engaging on a contingent credit financial instrument to cover certain risk layers, and purchasing insurance to transfer financial risk to a third party. The costs and benefits of different policy options or combinations of policy options (strategies) are calculated and the one that yields the highest ratio between benefits and costs is selected. Additionally, a budget constraint is introduced to reflect government budgets.

The original Investment Profile proposed a method based on the following stages:

1. Identification of risk mitigation measures (or ex-ante investment) and financial instruments (ex-post) applicable to the area under study;

2. Identification of a set of possible strategies, $S = (s_1, s_2, \ldots, s_n)$ derived from a combination of risk mitigation measures and financial instruments;

3. Identification of the costs and benefits related to each strategy;

4. Quantification of costs and benefits over time;

5. Comparison of the flows for costs and benefits through a B/C relationship, defined as: $\frac{B}{C} = (\text{Present value of the benefits})/(\text{Present value of the costs})$; and

6. Selection of the optimal strategy that yields the highest B/C ratio.

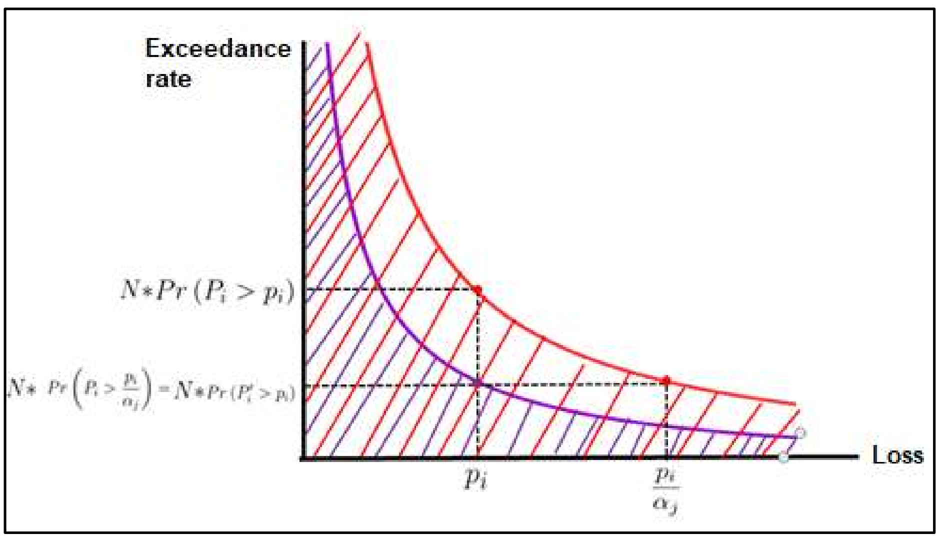

Figure 1. Comparison of the AAL between two Loss Exceedance Curves (initial and mitigated states). Source: Investment Profile (IDB, 2020)

Using the IP methodology entails calculating the benefits of the different DRM policy strategies using the differences in Loss Exceedance Curves (LECs) before and after DRM policy implementation (Figure 1). The benefit of each DRM policy option (or strategic combination of policy options) is estimated as the difference between the present values of

Average Annual Loss (AAL). The AAL before DRM policy intervention corresponds to the value without a risk mitigation measure or coverage from a disaster financing instrument (i.e., business-as-usual or "no policy" scenario), and the AAL after DRM policy is the residual risk after having invested in mitigation or risk retention/transfer. The overall benefits of the strategies, combining more than one option, is the sum of the individual benefits.

The costs of the risk mitigation measures are calculated based on civil and structural engineering analyses for risk mitigation when compiling the Investment Profile. The cost of acquiring any of the disaster financing instruments is associated with the layer of risk covered by each instrument. The Investment Profile chooses the optimal mix/combination of DRM interventions in two steps: 1) an end-user employing the model chooses the level of risk to be mitigated (low, medium, and high) and 2) based on the marginal cost minimization model of Mahul and Gurenko (2006), chooses an optimal mix of risk retention and transfer instruments.

The methodology used for assessing costs and benefits in the Investment Profile can be supplemented with important points for decision-makers. After comparing the existing investment profile methodology to related literature and models and critically examining its inputs and outputs including those found in the Peru country profile discussed in subsequent section 2.2, the following limitations can be identified:

- **Ad hoc estimation of indirect losses:** The Investment Profile study discusses direct damage and indirect losses of natural disasters and indicates that, in general, limited information is available regarding the magnitude of indirect loss in the Latin America and the Caribbean (LAC) region. To simplify the calculations, this methodology assumes that the total damages and losses (i.e., sum of direct damages and indirect losses) resulting from a hazard event is equal to 2 times the direct damage for events with a return period of 50 years and more, based on data from Benson (2012). The exact magnitude of indirect losses however depends on many factors including an economy's inter-industrial structure as well as behaviors of economic actors.
- **Limited incorporation of DRM benefits:** The Investment Profile study incorporates only the reduction of direct damage as a benefit of DRM investment. However, the recent literature on DRM investment (such as the previously discussed literature on triple dividends) increasingly emphasizes that DRM investment brings multiple benefits beyond mere reduction of damage, such as promotion of further economic productivity through increased savings and investment as well as additional environmental and social co-benefits.
- **Separation of DRR and risk financing investment:** The Investment Profile takes a two-step approach to the evaluation of DRM investment options whereby a model end-user chooses a desired level of DRR investment in the first step. A cost minimizing set of risk retention and transfer instruments are then selected in the 2nd step of analysis. This approach does not comprise a simultaneous assessment of allocating resources and therefore questions such as the quantity of resources to be allocated to DRR investment versus risk financing instruments cannot be fully answered.

The alternative method proposed in this study hence addresses these major limitations identified in the Investment Profile methodology.

2.2. Review of Country Case Study

Under the project TC RG-T2434: Development of Public Investment Profile in Disaster Risk Reduction (https://www.iadb.org/en/project/RG-T2434), the Investment Profile methodology was applied in selected countries at the national level (Bolivia, Honduras, and Peru) and one at the local level (Rio Rocha river basin in Bolivia). The Peru IP report (IDB, 2020a) applies the DRR Investment Profile methodology to identify the optimal DRR strategy combining ex-ante mitigation measures and ex-post financial instruments to address earthquakes and floods, which are the natural disasters incurring the largest annual losses in Peru.

Table 1 Parameter values of earthquake and flood mitigation measures.

Impact of the measure	Potential reduction of damages from earthquake	Cost (% of exposed value) of earthquake	Potential reduction of damages from flood	Cost (% of exposed value) of flood
Low	14% to 37%	3.3%	5% to 35%	3.5%
Medium	30% to 60%	6.2%	5% to 50%	3.7%
High	43% to 73%	8.2%	10% to 60%	4.0%

The Peru IP report (IDB, 2020a) uses three generic DRR measures with different mitigation efficiency levels: high, medium, and low. Measures with high mitigation efficiency are assumed to reduce the effects of disaster events with a return period of more than 100 years, medium efficiency measures reduce the effects of events with a return period between 50 and 100 years, and low efficiency measures reduce the effects of events with a return period of less than 50 years. Table 1 shows the values used in the case of Peru for the mitigation potential and cost of DRR measures for earthquakes and floods.[5]

In TC RG-T2434: Public Investment Profile in Disaster Risk Reduction, Loss Exceedance Curves (LECs) were developed under no mitigation for earthquakes and floods. Based on parameters shown in Table 1, the Investment Profile model calculated the variations in LECs under the three mitigation efficiency levels and their associated costs to arrive at the benefit/cost ratios of alternative DRR strategies that combine mitigation measures (no mitigation, low, medium, and high mitigation efficiency levels) and financial instruments, under various budgetary constraint scenarios.

Results of the Investment Profile analysis indicated that by implementing mitigation measures, damages related to earthquakes and floods could be reduced considerably. The benefit-cost ratio was found to be higher than for most strategies that include mitigation measures. The highest benefit-cost ratio was obtained with the implementation of mitigation measures only (BC ratio of 2.3 in case of low mitigation investment over a 5 year horizon and 3.8 over 10 year time horizon). The Investment Profile model identified that, in general, the

[5] The parameter values obtained from the Peru Investment Profile report are indicative and do not reflect modelled cost and benefits as DYNAMMICs does. The DYNAMMICs modelling approach replaces these types of rough preliminary values with endogenously modelled parameters determined within the model, not exogenously assumed.

benefit-cost ration decreases when financial instruments are included. Among those with financing instruments, the implementation of all three financial instruments together with high mitigation efficiency measure achieves the highest BC ratio (1.62 over a 5 year time horizon and 2.41 over a 10 year time horizon). Without mitigation, the strategy with the highest benefit-cost ratio should include all three financial instruments. The study also notes that investing in mitigation not only reduces the damage and losses that the country could potentially face, but also reduces the cost of the financial instruments because of the positive change in risk structure of the country. Moreover, the report identifies the optimal sectoral budget allocation for mitigation measures addressing earthquakes and floods.

2.3. Methodological Improvements Introduced in the Present Study

Based on the limitations identified above, this study proposes an improved modeling framework termed **Dyna**mic Model of **M**ultihazard **Mi**tigation **C**o-benefit**s** (DYNAMMICs), as an overarching macroeconomic framework to evaluate the costs and benefits of alternative public finance allocation among risk mitigation measures and financial instruments. This method builds on the basic conceptual framework of cost and benefit assessment as developed in the Investment Profile, while also strengthening the theoretical and methodological consistency of the interactions that are known to exist between disaster impact, DRM interventions, and the economy.

Table 2 summarizes major new contributions of DYNAMMICs to the existing Investment Profile methodology and common features. DYNAMMICs introduces several important conceptual improvements over the existing Investment Profile methodology.

Table 2. Summary of contributions and common features.

Contributions	Means of implementation
Endogenization of indirect loss calculation.	Estimation of GDP losses both at national and sector levels.
Estimation of multiple benefits of DRM investment (i.e. triple dividends)	Triple dividends are estimated as total growth effects, which may be decomposed of first, second and third dividends (please see section 3.2.2 for details).
Operationalization of risk layering concept (i.e. simultaneous evaluation of a large number of DRM strategies combining mitigation measures and financial instruments.) Quantification of the potential of investment in mitigation measures in improving the affordability and effectiveness of financial instruments.	DYNAMMICS include the DRR investment, and all risk-financing arrangements as government policy intervention options. Contingency credit and insurance arrangements are available from the international market (please see section 3.2.3 for details).

The first improvement is the endogenization of indirect economic loss estimates. This endogenization enables the assessment of not only the benefit of DRM investments in terms of the reduction in expected damages but also in terms of how DRM investment reduces expected losses of GDP in the long term via other channels.

The second improvement is the operationalization of the concept of the triple dividend introduced in detail in Section 3.2.2. In short, this concept includes three types of dividends created by DRM investments beyond mere damage mitigation. The dividends corresponding to the reduction of disaster impact (first dividend), fostering of economic potential in the economy experiencing DRM investments (second dividend), and other co-benefits of DRM investments for instance in environmental and social aspects (third dividend). Not including these dividends in a cost/benefit assessment of DRR investments (as is done in the Investment Profile methodology) leads to an underestimation of the benefits of the investments. The updated DYNAMMICs modeling method addresses this issue and thus reflects both direct and indirect benefits of DRR investments.

The third improvement is the operationalization of the risk layering concept within DYNAMMICs. Unlike the existing Investment Profile, which has taken a two-step approach using separate evaluation of the mitigation measures and both ex-post and ex-ante financial instruments, DYNAMMICs is designed to concurrently evaluate various DRM strategies, properly accounting for the interactions between different policy options.

3. Methodological Framework

3.1. Overview of DYNAMMICs

The simplified model flow in Figure 2 illustrates the major components of the assessment using the DYNAMMICs model. The dynamic macroeconomic model assesses the economic growth paths of an economy as a whole, taking into account multiple benefits of DRM interventions beyond mere reduction of direct disaster damages.

The DYNAMMICs model takes as inputs disaster and climate risk estimates from biophysical model assessments. These consist of, for example, 1) estimated probabilistic damages to labor availability based on the population exposed to hazards of alternative magnitudes; 2) probabilistic damages to infrastructure and capital (including private productive capital and natural capital) estimated based on spatially explicit catastrophe risk modeling, as well as 3) slow-onset changes such as coastal erosion damages due to climate change, assessed using coastal hazard and sea-level rise simulations. Damages in different types of assets can be mitigated by investing in alternative DRM policy options.

Two types of DRM policies are evaluated in the model: i) DRR Investments and ii) Risk Retention and Transfer Options. The model evaluates alternative policy mixes and assesses macroeconomic trajectories for each of the different mix of policies. The DYNAMMICs model jointly evaluates the effects of disaster risks and DRM policy interventions on the domestic and foreign sectors of the economy, thereby allowing for the comparison of macroeconomic variables before and after the implementation of DRM policies.

The comparison of macroeconomic variables such as Gross Domestic Product before and after DRM policy interventions can be considered as the indirect component of the total benefit of DRM policy - which can be disaggregated into the three dividends of: i) risk reduction, ii) promotion of growth through channels such as saving and investment and iii) environmental and social co-benefits.

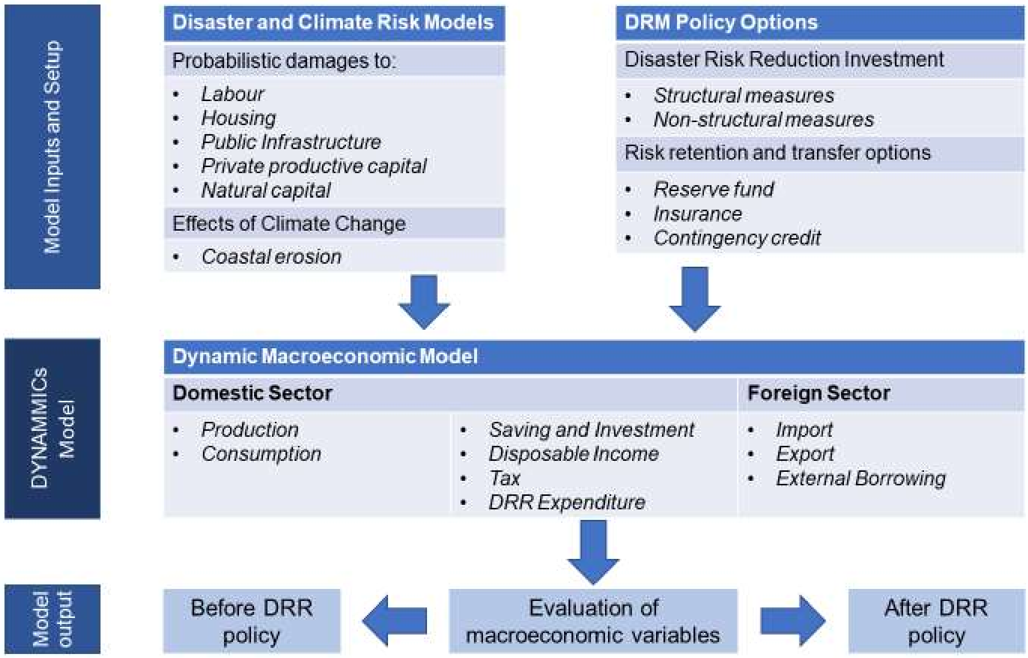

Figure 2. Model flow and components of the DYNAMMICs model

3.2. Theoretical Foundation of DYNAMMICs

3.2.1. DRM Investment in Macroeconomic Modeling

Economic evaluation of disaster and DRM investment is a part of the risk assessment literature composed by transdisciplinary integration of models in multiple areas (Hoffmann, 2011). Table 3 provides an overview of the different types of macroeconomic and public finance modeling tools used in disaster studies. Two major approaches are widely used in the literature and in practice. One approach consists of empirically-oriented models such as macroeconometric models used for ex-post assessment of policy and disaster shocks. Studies using this approach include Cavallo and Noy (2009), Klomp and Valckx 92014), and Lazzaroni and van Bergeijk (2014).

The alternative approach which is also used by DYNAMMICs are theoretically-oriented models calibrated empirically. This approach includes deterministic models that explicitly deal with market transactions, such as input–output (I-O) (e.g., Hallegatte, 2008; Santos, 2006; Hallegatte, 2014; Koks et al., 2015) and most Computational General Equilibrium (CGE) (e.g., Giesecke et al., 2012; Rose and Shu-Yi, 2005) modeling. As for dynamic frameworks, recent studies used dynamic macroeconomic models to evaluate the macroeconomic impacts of disasters in disaster-prone countries (Cantelmo et al., 2019) and in small developing states (Marto et al., 2019). Some studies pay exclusive focus to the behavior of financial markets (e.g., Barro, 2006, 2009; Gourio, 2008; Rietz, 1988; Wachter, 2013). Other studies include the impacts of disasters on real assets and production in dynamic models, such as the Dynamic Stochastic General Equilibrium (DSGE) model (e.g., Keen and Pakko, 2007; Posch and Trimborn, 2011; Segi et al., 2012) and the endogenous business cycle model (Hallegatte and Ghil, 2008; Hallegatte et al., 2007).

Moreover, several models that are associated with market disequilibrium have been recently used in disaster studies including agent-based models such as Austria ABM (Hochrainer-Stigler and Poledna, 2016; Poledna et al., 2019) and system dynamics models such as the Binary constrained Disaster (BinD) model (Dunz et al., forthcoming). Theoretically-oriented models include also public finance models such as the Catastrophe simulation model (CATSIM) (Mechler et al., 2006; Hochrainer, 2006).

3.2.2. Multiple Benefits of DRM Investment

The latest literature on the economics of DRM investment (e.g. Ishiwata and Yokomatsu, 2018) increasingly emphasizes that DRR investment protects productive assets and lives and, when implemented wisely, yields multiple other benefits. Such benefits are increasingly referred to as "multiple dividends" or triple dividends (Tanner et al., 2015), namely:

- The 1st dividend – **reducing disaster impact.** DRM investments reduce immediate disaster impacts (human loss/injuries, infrastructure damages and other economic impacts);

- The 2nd dividend – **fostering economic potential.** DRM investments foster a safer environment for investment and enhanced economic activities (e.g., increasing business and capital investments, as well as savings, increasing fiscal stability and access to credit);

- The 3rd dividend – **producing co-benefits.** DRM investments produce additional co-benefits (e.g., environmental and societal benefits).

DYNAMMICs is designed to account for these three types of benefits associated with DRR investment. These benefits can be estimated with regards to the economic (GDP) growth effects of DRR investment on disaster risk reduction (as introduced in Ishiwata and Yokomatsu 2018) and to its co-benefits (introduced in UNDRR 2020).

These growth effects of DRR investment are termed:

- ***Ex Post Damage Mitigation Effect (PDME)*** - corresponding to the 1st dividend of DRM;

- ***Ex Ante Risk Reduction Effect (ARRE) -*** corresponding to the 2nd dividend of DRM;

- ***Co-benefit Production Expansion Effect (CPEE) -*** corresponding to the 3rd dividend of DRM

Table 3. Types of macroeconomic and public finance modeling tools

Types of models	Advantages	Limitations	References
Empirically-oriented models *Statistical Models driven by data and some simplifying assumptions*			
Macro-econometric model	▪ Flexibility and ease of implementation. ▪ Suited for testing of theoretical assumptions, ex-post assessment of policy and disaster shocks.	▪ Series of empirical observations following disaster shocks and introduction of policies are needed (catastrophe event samples are rare). ▪ Econometric models are limited in the amount of detail they can represent. This sometimes impedes theoretical interpretation of choices and market transactions, resulting in limited predictive power; they only provide a quantitative forecast within the same direction of past experience.	Cavallo and Noy (2009); Klomp and Valckx (2014); Lazzaroni and van Bergeijk (2014).
Theoretically-oriented models (calibrated empirically) *Mathematical models built on economic theory and adapted to reflect real-world numbers*			
Equilibrium-based models (where all markets represented in the mathematical model need to be in equilibrium)			
Non-stochastic macroeconomic models (IO/CGE/SAM)	▪ Less intensive data requirements, ease of implementation (including computational needs). ▪ Most models in this category focus on a state or process after a disaster occures. Static models simulate resource allocation after the environmental change (as a new equilibrium), while dynamic models simulate recovery process usually with a concern on evaluation of reconstruction policies. ▪ Suited for the ex-ante analysis of policy and disaster shock.	▪ Unsuited for the analysis of transition and out-of-equilibrium dynamics such as immediate post disaster recovery trends. ▪ Because they do not deal with random arrivals of disaster, they are not capable of analyzing ex-ante (pre-disaster) resource allocation such as investments in production and disaster mitigation, and making of financial portfolio including insurance, bond, etc.	An adaptive regional input-output model (ARIO) (Hallegatte 2008); Inoperability Input-Output Model (Santos 2006); For review of additional CGE/IO models, see (Galbusera and Giannopoulos, 2018; Zhou and Chen, 2020).
Stochastic macroeconomic models (DSGE)	▪ Due to a dynamic framework, they are suited for the ex-ante analysis of disaster-risk-reduction (DRR) policies and alternative macroeconomic behaviors (i.e. preparedness) under risk. ▪ Results based on the rational expectation hypothesis are characterized as the normative solution that serves as a benchmark in policy discussion. ▪ DSGE models are also applied mainly with a purpose of macro-econometric verification based on past time-series data	▪ High computational needs. ▪ Unsuited for the analysis of transition and out-of-equilibrium dynamics such as immediate post disaster recovery trends. ▪ In cases that they are applied to predict the far future and possibility that unpredictable changes of technologies and other environment could happen in the process is pointed out, predictability of the models is questioned.	Dynamic Model of Multihazard Mitigation Co-benefits (DYNAMMICs), Others include (Cantelmo et al., 2019; Marto et al., 2019).
Non-equilibrium-based models (Focusing on individual behavior or capital flows and assuming no perfect equilibria on markets)			
Agent-based models	▪ Flexibility of model set-up (including high levels of geographical, sectoral and temporal disaggregation possibility, heterogeneity of economic agents). ▪ Suited for the ex-ante analysis of emergent/non-linear dynamics stemming from the interactions of individual economic agents (possible to model immediate recovery and longer-term recovery trends).	▪ High computational and data needs. ▪ Difficulty in interpretation of modeling output due to complex dynamics.	Austria ABM (Poledna et al., 2019)
System dynamics (stock-flow consistent models)	▪ Flexibility of model set-up and less computational needs, ▪ Suited for the ex-ante analysis of feedback and non-linear dynamics stemming from the interactions of macroeconomic (and financial) variables (possible to model immediate recovery and longer-term recovery trends).	▪ Less geographical/sectoral disaggregation is possible (relative to modeling approaches such as ABM).	Binary constrained Disaster (BinD) Model (Dunz et al., forthcoming).
Public finance and risk financing models (With a focus on public spending needs and limited incorporation of other economic dynamics)			
Catastrophe simulation models for public finance	▪ Less intensive data requirements, ease of implementation (including computational needs). ▪ Suited for the ex-ante analysis of policy and disaster shock.	▪ Limited incorporation of macroeconomic dynamics.	Catastrophe Simulation (CATSIM) (Mechler et al., 2006, Hochrainer, 2006)
Resource gap risk financing model	▪ Possibility to identify single best ex-ante financing instrument	▪ No incorporation of macroeconomic dynamics ▪ Does not allow incorporation of risk sharing agreements	(Mahul and Gurenko, 2006)

PDME describes the difference between the magnitude of a disaster shock to the macroeconomy with and without DRR investment. **ARRE**, on the other hand, shows the benefit of DRM investment even in absence of disasters in terms of fostering other productive investments, thereby increasing GDP. **ARRE** becomes positive when DRM investment safeguards further economic gains to be made from other productive investments. In economic terms, DRM investment increases the shadow value of other productive investments.[6] These increases in shadow values can occur through the longer-term effectiveness of DRR investments such as increased propensity of households to save and invest, additional entrepreneurship promotion, and increased innovation and incentives among firms to take risks and invest (Tanner et.al., 2015). It is important to note that a country benefits from **ARRE** regardless of whether disaster shocks occur in a simulated time period. **CPEE** describes the additional co-benefits that could be produced as a result of DRM investment, such as ecosystem services and other societal benefits.

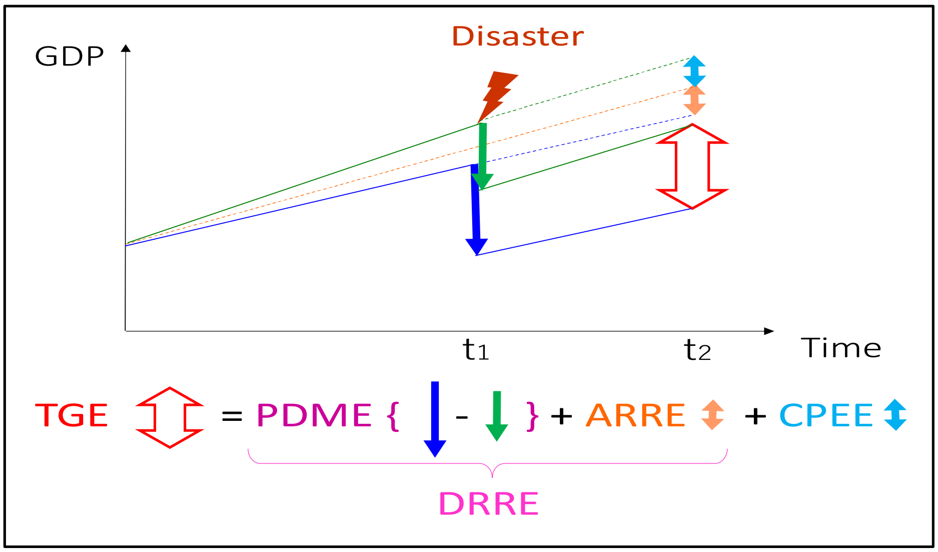

Figure 3. Decomposition of Total Growth Effect (TGE).

Figure 3 illustrates the multiple benefits that could be provided by DRM investment. The green and blue solid lines represent GDP paths with and without a DRM investment policy, respectively. GDP drops at time t_1 following a disaster event. On the other hand, the green and blue dashed lines represent GDP paths in the hypothetical case where the disaster did not occur at time t_1. Thus the effect of DRM investment at the end of the planning period t_2 can be evaluated. The Total Growth Effect (TGE) of the policy in terms of GDP is decomposed into Disaster Risk Reduction Effect (DRRE) and Co-benefit Production Expansion Effect (CPEE), where DRRE is composed of PDME and ARRE. Since CPEE is

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[6] Shadow value refers to a concept used in mathematical optimization. It quantifies the price associated with investments in the hypothetical case they could be increased. The price can be interpreted as the willingness to pay for an additional unit of investment if the budget constraint on investment could be increased by one unit. In other words, shadow prices can also be seen as reflecting the marginal contribution of a variable to a payoff. This definition is adapted from Fuente (2000); see p. 568 for a discussion of the concept of shadow value in dynamic optimization.

obtained in non-disaster times, the sum of ARRE and CPEE is a benefit that is obtained even without an actual disaster event.

3.2.3. Risk Layering Disaster Risk Financing Strategy

An additional innovative aspect of the proposed DYNAMMICs model is that it captures the concept of risk-layering strategies. Figure 4 graphically depicts the "risk-layering concept", showing the potential interaction between DRR investment and the risk retention/transfer instrument. While the DRR investment decreases the magnitude of damages, the drop in the magnitude of damages leads to a reduction in the cost of acquiring risk retention and transfer instruments. DRR investment thus allows governments to more easily access these disaster risk financing policy options.

In DYNAMMICs, the DRR investment and all risk-financing arrangements will be included as government policy interventions. Contingency credit and insurance arrangements will be available from international markets.

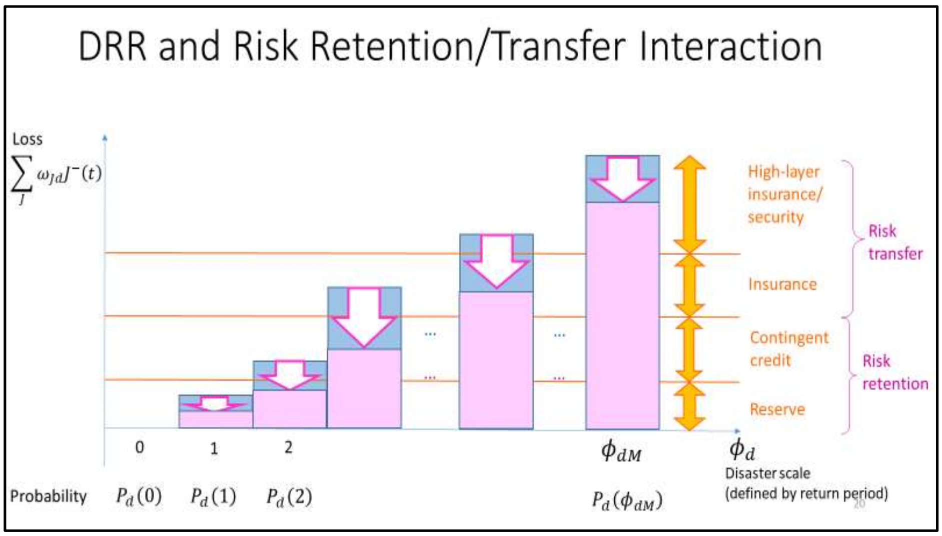

Figure 4. Risk Layering to be included in the dynamic macroeconomic framework.

4. A general framework for linking DYNAMMICs to DRR Investment Profile

The general structure of the model is illustrated in Figure 5. DYNAMMICs is a dynamic macroeconomic model that captures a forward-looking rational expectation of a representative household and firm, whose perception of future earnings and losses are affected by the prevailing levels of multiple types of disaster risks and DRM investment. The changes in expected utility of households and expected profit of production sectors affect other aspects of economic activities such as optimal levels of savings and investment, demand for labor and capital, shares of import/export, and ultimately a country's GDP growth trajectory. DYNAMMICs is capable of quantifying the macroeconomic costs and benefits of investment in DRM (i.e., mitigation and risk financing), including how the provision of safer environments fosters increases in investments and private savings as well as how multi-purpose DRR investments bring co-benefits such as the improvement in public services provision and other socioeconomic gains.

This study uses the second version in the series of DYNAMMICs models with a focus on non-traded goods such as services, local cultures, and natures, which also incorporates the concept of risk-layering of fiscal policy for disaster risk reduction. The first version DYNAMMICs model was applied to countries such as Angola, Tanzania, and Zambia (UNDRR, 2020), where hazards were specified as floods and droughts, and the two main sectors consisted of an agricultural and a composite-good (i.e. non-agricultural) sectors. Drought impacts on agriculture were an important focus of the analysis of this first version. The second version is adapted to reflect other risks and economic sectors. This model is a customization of the second-version DYNAMMICs model, where two types of lands are identified, namely coastal areas and inland areas.

As is illustrated in Figure 5, DYNAMMICs depicts the circular flow of a two-sector economy consisting of traded and non-traded goods sectors[7] that are exposed to both rapid and slow onset hazards. The model is formulated using a dynamic stochastic optimization framework, which allows one to examine what is known as the stock formation process (i.e., how an economy´s productive capital may accumulate over time both during normal and post-disaster times). The framework facilitates an analysis of how a society may undergo a recovery process from one disaster, while also being exposed to the risk of the next disaster. Also, the model allows for an evaluation of optimal resource allocation in that if the government allocates too much investment in production infrastructure rather than for DRR infrastructure, the society will suffer from severe damages and losses repeatedly. The stock control problem is formulated under random arrivals of disasters, to analyze the best allocation of resources between production (i.e. reconstruction of production infrastructure) and disaster mitigation. A detailed description of each of the several components DYNAMMICs includes is provided in the following sub-sections.

Note that this study applies a simulation strategy including approximation and simplification of the optimization framework, which will be briefly explained in section 14.6.

[7] In simple economic-model frameworks, tourism has been conceptually defined by "foreigners' demand for non-traded goods/services", implying that while "traded-good sectors" can extend their markets to foreign countries by trade, it is an essential role of tourism that extends the market size of "non-traded good/service sectors". "Non-traded good/service" is sometimes called "home good/service" for that reason, which travelers visit and enjoy "on site". Tourists not only enjoy services based on local culture but also use public transportations, go to hospitals, etc. They can theoretically take almost any service that local residents take (although demand shares are usually different between tourists and residents). For that reason, this model starts with identifying two sectors by Traded and Non-traded sectors and then evaluates an impact on Non-traded good sector in order to quantify disaster impacts on tourism. However, if the study finds that the model specification by "Tourism/Non-tourism sector" is more reasonable due to data or other factors, the study model may update the framework accordingly.

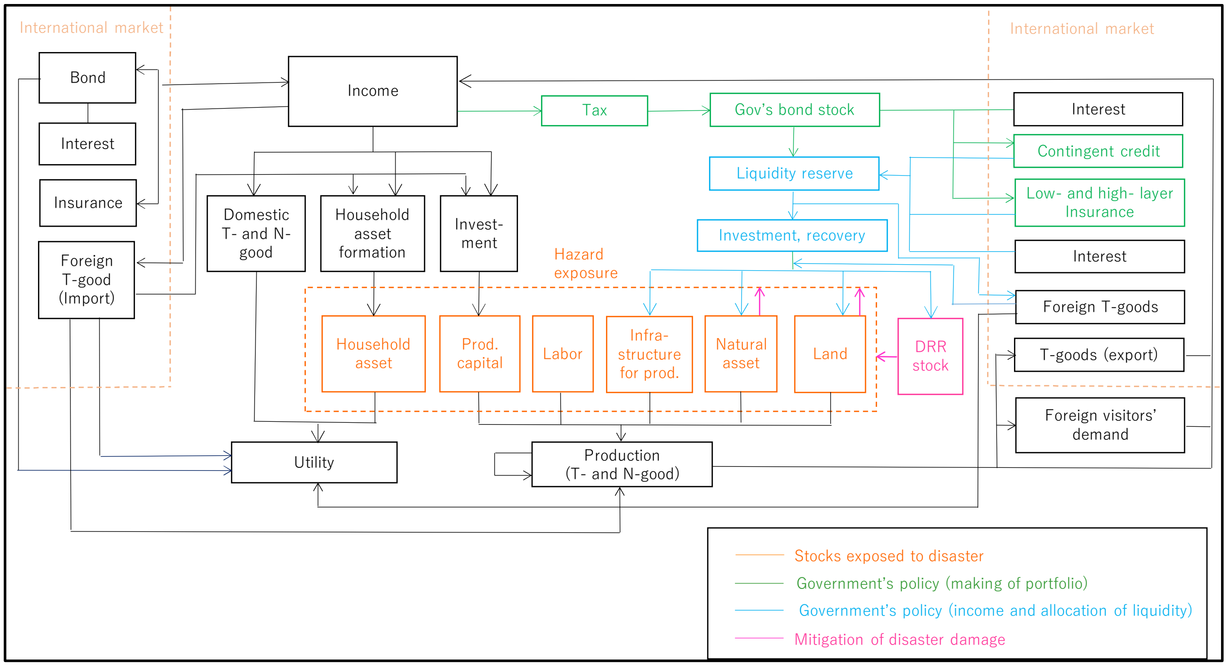

Figure 5. The standard structure of the DYNAMMICs model.

4.1. Markets

In DYNAMMICS, the representative economy consists of one country that is composed of two spatial areas, two business sectors, and an open economy. All markets are assumed to be perfectly competitive under symmetric and perfect information. The two spatial areas are inland and coastal areas as hazard risks tend to differ considerably between these two geographical areas, while the two sectors are Traded and Non-traded good sectors. The two types of goods are used for intermediate inputs of production, investment, and consumption in the country. Traded goods are also exported to economic agents in foreign countries. A Traded good produced in the country is different from one produced in foreign countries, and not perfectly substitutable with each other (Hereafter, for notational convenience, "Traded good" means "Domestic Traded good"). Although Non-traded goods are not exported, they are demanded by foreign visitors. Hence, "tourism" expands the Non-traded good market in terms of total demand.

Foreign bond is traded in the international market and functions as a financial vehicle for lending and borrowing. Moreover, disaster insurance is assumed to be provided by a foreign insurer, and available for households in the country.

Government imposes taxes and takes out loans by issuing government bonds in the international market to finance its investments. Public spending is used for purposes such as infrastructure for production, disaster risk reduction (DRR stock), risk finance and recover investments in land and natural assets from their disaster impact, and purchase foreign relief goods at disaster times. The government's fiscal state is defined by two-dimensional stock variables: positions of government bonds and liquidity reserves. While long-term borrowing and lending are managed on the account of government bonds, all government expenditure is mediated by the reserved liquidity. In other words, while the government can go into debt by making the position of government bonds negative, it is always faced with a "cash-in-advance constraint", implying that it should keep positive liquidity to cover its expenditure. In order to meet prompt needs of liquidity after a disaster, the government has a set of special contracts with banks and insurers which is called "risk layering approach", discussed in detail in the subsequent section.

The number of households (i.e., domestic households) grows at a constant rate. The labor market is closed within the country, with inelastic labor supply from households. Households (hereafter referred to as Domestic households) are assumed to have an infinite time horizon, to be identical, forward looking, and rational, with perfect perception of disaster risks and schedules of policies, and to maximize expected lifetime utility.

Under these assumptions, the economy achieves the Pareto-optimal allocation.[8] In this allocation no household can increase their utility without decreasing the utility of at least one other household. Therefore, it can be solved by dealing with "the planning problem," in which one representative agent (i.e., a household) allocates all the resources over an infinite time horizon to maximize household lifetime expected utility, describing the equivalent allocation in a competitive equilibrium (Stokey, Lucas, & Prescott, 1989). For instance, a household maximizes their utility resulting from income, leisure and their preferences such as risk aversion under budget constraints. Following most Real Business Cycle (RBC) models, we deal with the equivalent first-best problem.

4.2. Technology and population growth

The model economy grows both by endogenous capital deepening and exogenous technical progress. The amount of capital per worker in the economy is therefore determined inside the model by the economic dynamics (capital deepening) while the change in technology is assumed to be resulting from research and development (R&D) which is not determined by variables included in the model. Although a main concern is the way the growth of per worker capital is affected by disaster risk reduction (DRR) policy implementation, it is also recognized that technological progress is quantitatively non-negligible. An example is progress in an area of information systems, where most new ideas are developed overseas.

This study assumes *Harrod-neutral technical progress* which is considered standard in the economics literature, increases the efficiency of labor and does not directly augment the efficiency of capital inputs. The notion of labor-augmenting technology as used here is based on the dynamics described in the Harrod-Domar model of economic growth (Harrod, 1939 and Domar, 1946). Let $A(t)$ be the Harrod-neutral technology level, and $L(t)$ be the total amount of labor, that is, the total number of households. Now the labor force in efficiency units is given by the product $A(t)L(t)$, and increases faster than the number of workers, $L(t)$. Thus, technical progress of this form is characterized by labor-saving.

[8] "In a Pareto efficient allocation of goods, no one can be made better off without making someone else worse off. The term Pareto efficiency is named after the Italian economist Vilfredo Pareto, who developed the concept of efficiency in exchange. Notice, however, that Pareto efficiency is not the same as economic efficiency […]. With Pareto efficiency, we know that there is no way to improve the well-being of both individuals (if we improve one, it will be at the expense of the other), but we cannot be assured that this arrangement will maximize the joint welfare of both individuals." (Pindyck and Rubinfeld, 2017)

The standard assumption of growth models assumes that $A(t)$ and $L(t)$ develop with the constant growth rates, ζ_A and ζ_L, respectively, as follows[9]:

$$A(t+1) = A(t) \cdot (1+\zeta_A), \quad A(0) = 1 \qquad (1a)$$
$$L(t+1) = L(t) \cdot (1+\zeta_L), \quad L(0) = L_0 = 1\ (standardized) \qquad (1b)$$

4.3. Hazards

Let $t = 0,1,\cdots$ be a period of time whose unit is given by a year. The model assumes two kinds of hazards: fast and slow-onset hazards. The former includes hurricanes and earthquakes, for example, that destroy physical stocks in economy once arrived, while the latter may include beach erosion, mangrove forest reduction, soil contamination. In what follows, the model calls the former "disaster", and the latter, "environmental change" for convenience.

The scale of disaster in Period t is represented by a random variable ϕ_t that can take one value out of a set $\{0, 1, \cdots, \phi_{max}\}$ where $\phi_t = 0$ represents a case of no disaster damage in Period t. Note that, ϕ_t represents the sum of damage in one period especially in cases where the probability that disasters occur more than twice is not negligible. $P_H(\phi)$ represents the probability of disaster of the scale ϕ. Thus, $\sum_\phi P_H(\phi) = 1$ holds. A stable stochastic process of disaster is assumed here meaning that probabilities $\{P_H(\phi) | \phi = 0,1,\cdots,\phi_{max}\}$ do not change over time.

Environmental change deteriorates stocks of land and natural assets, $Z_\iota(t)$ and $N_\iota(t)$, respectively. It is formulated by a combination of the trend terms, $(-\delta_{Z\iota})$ and $(-\delta_{N\iota})$, and the volatility terms, $\sigma_{Z\iota}\varepsilon_{Z\iota\,t}$ and $\sigma_{N\iota}\varepsilon_{N\iota\,t}$, where $\varepsilon_{Z\iota\,t}$ and $\varepsilon_{N\iota\,t}$ are white noises, σ damage rates as shown in equation (3b).

4.4. Physical stocks

The model incorporates multiple stocks of economic variables, levels of which change over time. Letting J_ι be stock $J\,(= K, H, G, Z, N, D)$ in area $\iota\,(= I, C)$, where K represents firms' production capital, and H household assets, G infrastructure for production, Z land, N natural asset, D facilities for disaster risk reduction ("DRR stock"). Two areas are denoted by $\iota = I, C$, where I are inland and C are coastal regions.

For $J = K, H, G$, and $\iota = I, C$, the formation process is given as follows:

$$J_\iota^-(t+1) = \left(1 - \delta_{J\iota}\right) J_\iota(t) + L(t)\eta_{J\iota}(t) \qquad (2a)$$

---

[9] Solving and computing the set of problems incorporated in the model requires several modelling techniques. Among them the transformation of the model into a version composed of the effective labor unit to detrend the model with the intent of preventing variables from diverging to infinity. Variables of the effective labor unit are obtained by dividing their (original) total values by $A(t)L(t)$. The following general notation rule applied to state and decision variables in the dynamic optimization problem is introduced for ; that is, for an arbitrary variable $X(t)$: 1) the (original) totalized value is denoted by a capital letter, $X(t)$; 2) the variable of the amount per household is denoted by a small letter $x(t)$, defined by $x(t) = X(t)/L(t)$; and furthermore 3) the variable of the amount per effective labor (a variable of the effective labor unit) is denoted by a small letter with tilde $\tilde{x}(t)$, namely, $\tilde{x}(t) = x(t)/A(t) = X(t)/\{A(t)L(t)\}$. Note that the above rule is not applied to prices, most parameters, and policy indices. Exceptions from this notational convention are clearly marked.

$$J_\iota(t+1;\phi_{t+1}) = \left(1-\omega_{J\iota\phi}\right)J_\iota^-(t+1) \quad \text{(2b)}$$

where $J_\iota^-(t+1)$ represents the stock level at the beginning of Period $t+1$ and before a disaster arrives, while $J_\iota(t+1;\phi_{t+1})$ represents its level after disaster of the scale ϕ_{t+1} arrives. δ_{J_ι} is the depreciation rate, $L(t)$ the total number of households, and $\eta_{J_\iota}(t)$ the per-household investment in stock J_ι in Period t. $\omega_{J\iota\phi}$ is the damage rate caused by disaster of the scale ϕ_{t+1}, and depends on the levels of other stock variables such as DRR stock, which will be explained subsequently. Equation (2b) shows that a part of stock is lost by being hit by disaster.

For $J = Z, N$ (land and natural assets) and $\iota = I, C$, the formation process is given as follows:

$$J_\iota^-(t+1) = \left(1-\delta_{J\iota}\right)J_\iota(t) + \tilde{\eta}_{J\iota}(t) \quad \text{(3a)}$$
$$J_\iota(t+1;\phi_{t+1}) = \left(1-\omega_{J\iota\phi}+\sigma_{J\iota}\varepsilon_{J\iota\,t+1}\right)J_\iota^-(t+1) \quad \text{(3b)}$$

where $\tilde{\eta}_{J_\iota}(t)$ represents investment per effective labor unit. Equation (3b) indicates that the stock is exposed to fluctuations caused by two random factors, $\omega_{J\iota\phi}$ and $\varepsilon_{J\iota\,t+1}$.

For $J = D$ (the DRR stock) and $\iota = I, C$, the formation process is assumed to be as follows:

$$D_\iota^-(t+1) = (1-\delta_{D\iota})D_\iota(t) + L(t)\eta_{D\iota}(t) \quad \text{(4a)}$$
$$D_\iota(t+1;\phi_{t+1}) = D_\iota^-(t+1) \;\; for\ any\ \phi_{t+1} \quad \text{(4b)}$$

that is, this model assumes that DRR stock is not damaged by disasters.[10]

As for the technology level $A(t)$, and the total amount of labor $L(t)$, that can also be regarded as a part of stocks in society, the technology level $A(t)$ is not affected by disaster, while the amount of labor $L(t)$ is reduced to be $\left(1-\omega_{L\phi}\right)L(t)$ in the period of disaster of the scale ϕ, but will recover itself without cost by the end of each period.

4.5. Disaster damage and mitigation

As mentioned above, a disaster of the scale ϕ brings damages on each stock $\omega_{J\iota\phi}$, which is mitigated by disaster risk reduction (DRR) policy implementation. The model incorporates multiple DRR measures applicable to a target disaster in a country including: 1) installation of structural measures ("DRR stock"), D_ι, that consist of several artificial facilities; 2) widening of area or mitigation erosion in a case such as beach, Z_ι; and 3) planting and maintaining native vegetation such as mangrove forest or coral reef, N_ι. In this model, the last two options are interpreted as "nature-based solutions" for disaster mitigation. The damage rates of stocks are given by a function of such stocks like

$$\omega_{Jl\phi} = \Omega_{Jl\phi}\left(\{D_\iota, Z_\iota, N_\iota\}_{\iota=I,C}, J_l^-\right) \quad \text{(5)}$$

[10] This is of course a simplification of the more complex dynamics that exist between hazard and DRR structures where DRR structure may be damaged in case of events exceeding design standards. This assumption was included to reduce the computational burden.

for production capital ($J = K$), household asset ($J = H$), infrastructure for production ($J = G$), area of land ($J = Z$), natural asset ($J = N$), and labor ($J = L$), and for inland area ($\iota = I$) and coastal area ($\iota = C$).

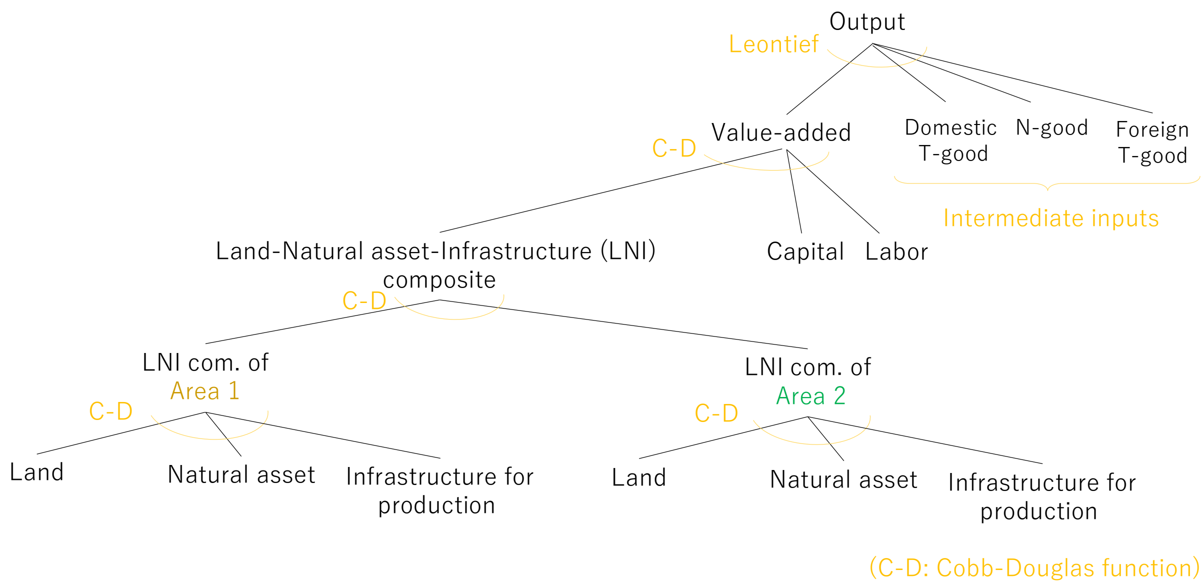

Figure 6. Nested structure of production technology.

4.6. Production technologies

The economy´s domestic production activities are expressed in a series of equations known as the nested production function structure illustrated in Figure 6. Production technologies of the Traded-good sector ($i = T$) and the Non-traded-good sector ($i = N$) are given by the following equations:

$$Y_i = \left[F_i(\cdot),\ \frac{Y_{Ti}}{\kappa_{Ti}}, \frac{Y_{Ni}}{\kappa_{Ni}}, \frac{Y_{Tfi}}{\kappa_{Tfi}} \right], \tag{6a}$$

$$F_i(\cdot) = \alpha_i(1 + \sigma_i \varepsilon_t)\{(1 - \omega_{L\phi})A(t)L_i(t)\}^{\alpha_{Li}} K_i(t)^{\alpha_{Ki}} X_{i\phi}(t)^{\alpha_{Xi}} \tag{6b}$$

where $F_i(\cdot)$ is the value added function. Y_{Ti} , Y_{Ni}, and Y_{Tfi} are intermediate inputs of (domestic) T-good, (domestic) N-good, and foreign T-good, respectively, while κ_{Ti}, κ_{Ni}, and κ_{Tfi} are their input-output coefficients. Total factor productivity (TFP) of the value added function is assumed to include a random shock, ε_t, as a white noise. $L_i(t)$ and $K_i(t)$ are labor and capital rented by sector i. $X_{i\phi}(t)$ represents the functional level of the land-natural asset-infrastructure (LNI) composite under the disaster scale ϕ, whose structure is assumed by Eqs. (7a) and (7b) below. α_i and σ_i are scale parameters, and α_{Li}, α_{Ki}, and α_{Xi} are share parameters of standard growth model Cobb-Douglas technology. Where the sum of the factor shares α for all inputs is unity. $X_{i\phi}(t)$ is assumed to be composed as follows:

$$X_{i\phi}(t) = X_{iI\phi}(t)^{\alpha_{XiI}} X_{iC\phi}(t)^{\alpha_{XiC}} \tag{7a}$$

$$X_{i\iota\phi}(t) = X_{i\iota 0}\{A(t)L(t)Z_\iota(t,\ \phi_t)\}^{\alpha_{iZ\iota}}\{A(t)L(t)N_\iota(t,\ \phi_t)\}^{\alpha_{iN\iota}}\{G_\iota(t,\ \phi_t)\}^{\alpha_{iG\iota}}$$

$$= X_{\iota 0}\left\{A(t)L(t)\cdot\left(1-\omega_{iZ\iota\phi}\right)Z_\iota^-(t)\right\}^{\alpha_{iZ\iota}}\left\{A(t)L(t)\cdot\left(1-\omega_{iN\iota\phi}\right)N_\iota^-(t)\right\}^{\alpha_{iN\iota}}\left\{\left(1-\omega_{iG\iota\phi}\right)G_\iota^-(t)\right\}^{\alpha_{iG\iota}} \quad (for\ \iota = I, C) \tag{7b}$$

α_{XiI}, α_{XiC}, $\alpha_{iZ\iota}$, $\alpha_{iN\iota}$, and $\alpha_{aG\iota}$ are share parameters where $\alpha_{XiI} + \alpha_{XiC} = 1$ and $\alpha_{iZ\iota} + \alpha_{iN\iota} + \alpha_{aG\iota} = 1$. $X_{\iota 0}$ is a scale parameter. $A(t)L(t)$ are applied as multipliers for technical reasons to deal with the per-effective-labor unit in the calculation process. It is emphasized that the level of LNI composite is stochastic because land, natural assets, and infrastructure for production are exposed to disaster at every time period.

4.7. Composition of capital good

All three goods: T-good, N-good, and foreign T-good, are used for investment. Investment good, which is turned into capital good, is composed so that it minimizes the cost of investment $\eta_{J\iota}(t)$ in each period t, namely, for $J = K, H, G, Z, N, D$, and $\iota = I, C$

$$p_T(t)\eta_{J\iota T}(t) + p_N(t)\eta_{J\iota N}(t) + p_{Tf}\eta_{J\iota Tf}(t) \tag{8a}$$

$$Subject\ to\quad \eta_{J\iota T}(t)^{\alpha_{\eta T}}\eta_{J\iota N}(t)^{\alpha_{\eta N}}\eta_{J\iota Tf}(t)^{\alpha_{\eta Tf}} = \eta_{J\iota}(t) \tag{8b}$$

where $\eta_{J\iota}(t)$ is the level of investment in stock $J\iota$, and Eq.(8b) represents how it is "produced" by combining the three original goods: $\eta_{J\iota T}(t)$, $\eta_{J\iota N}(t)$ and $\eta_{J\iota Tf}(t)$, that are T-good, N-good, and foreign T-good, respectively. $p_T(t), p_N(t)$, and p_{Tf} are prices of T-good, N-good, and foreign T-good in period t. p_{Tf} is assumed to be constant throughout, therefore notation "(t)" is not attached to p_{Tf}. While the level of investment, $\eta_{J\iota}(t)$, is determined in the dynamic optimization problem, the problem (8a)-(8b) takes $\eta_{J\iota}(t)$ as a given, and introduces the optimal levels of inputs for investment in the following way:

$$\eta_{J\iota i}(t) = \frac{\alpha_{\eta i}}{p_i(t)}\cdot p_\eta(t)\cdot\eta_{J\iota}(t) \quad (for\ i = T, N, Tf) \tag{9}$$

where

$$p_\eta(t) = \prod_{i=T,N,Tf}\left(\frac{p_i(t)}{\alpha_{\eta i}}\right)^{\alpha_{\eta i}} \tag{10}$$

is the effective price of capital good in Period t. The minimized cost of investment, $\eta_{J\iota}(t)$, is given by $p_\eta(t)\eta_{J\iota}(t)$.

4.8. Household's disaster insurance

All firms are assumed to be owned by households, who prepare against disaster damage by making insurance contracts on production capital, $K_\iota(t)$, and household asset, $H_\iota(t)$, with an insurance company on the international market. Insurance is defined by the following set:

(insurance premium, {Insurance money for the scale-ϕ-disaster})

$$=\left(p_\eta(t)\xi_{J\iota}(t)\Xi_{J\iota}(t)J_\iota(t), \left\{p_\eta(t)\omega_{J\iota\phi}(t)\Xi_{J\iota}(t)J_\iota(t) \mid \phi = 0,1,\cdots,\phi_{max}\right\}\right) \quad (for\ J = K, H, and\ \iota = I, C), \tag{11}$$

where $p_\eta(t)$ is the current price of the capital good by which the current values of stock damage are valuated. $\Xi_{J\iota}(t)$ $\left(0 \le \Xi_{J\iota}(t) \le 1\right)$ is the insurance coverage that households determine every period to have $\Xi_{J\iota}(t)J_\iota(t)$ insured. Therefore, if the stock is damaged at rate $\omega_{J\iota\phi}(t)$, insurance payouts $p_\eta(t)\omega_{J\iota\phi}(t)\Xi_{J\iota}(t)J_\iota(t)$ are released to households. Finally, $\xi_{J\iota}(t)$ is the premium rate that is determined by:

$$\xi_{J\iota} = \xi_{0J\iota} \sum_{\phi} P_H(\phi)\omega_{J\iota\phi}(t) \tag{12}$$

where ξ_{0J} (≥ 1) is a parameter that represents the risk premium or the mark-up rate in the insurance market. If $\xi_{0J\iota} = 1$, the insurance system would be fair. However, due to a peculiar feature of the disaster insurance market, that is, coincidence of large-scale insurance claims that could drive insurers into insolvency, insurers request a larger risk premium to prepare for the risk of simultaneous claims. Thus, $\xi_{0J\iota}$ is usually not set at one but larger.

4.9. Household's financial stock formation

Households can save and invest to manage timings of expenditure. They can go into debt within a certain range. Such an intertemporal value management is implemented by transacting foreign bonds on the international market where an interest rate is exogenously given and assumed to be constant. This intertemporal smoothing through bond transaction is mathematically equivalent to management on a bank account. Moreover, by aggregating over all countries, the position of the aggregated foreign bond stock is equivalent to the level of households' net foreign assets. Let $B_H(t)$ be the position of the total foreign bond that all households stock in Period t, and its sign be consistent with asset accumulation. The capital formation process of the households is represented as follows:

$$\begin{aligned} B_H^-(t+1) = {} & (1+r)B_H(t) + GDP(t) - p_T(t)Q_T(t) - p_{Tf}Q_{Tf}(t) - p_N(t)Q_N(t) \\ & -L(t)\tau(t) - p_\eta(t)L(t) \sum_{J=K,H} \left[\sum_{\iota=I,C} \eta_{J\iota}(t) \left\{ 1 + \Gamma_{J0} \right.\right. \\ & \left.\left. \cdot \left(\sum_{i=T,N,Tf} \left(\alpha_{\eta i}\right)^2 \right) \left(\frac{p_\eta(t)\eta_{J\iota}(t)}{j_\iota(t)} \right) \right\} \right] \\ & -p_\eta(t)L(t) \sum_{J=K,H} \sum_{\iota=I,C} \xi_{J\iota}(t)\Xi_{J\iota}(t)j\iota(t+1) \end{aligned} \tag{13a}$$

$$B_H(t+1;\phi_{t+1}) = B_H^-(t+1) + p_\eta(t)L(t) \sum_{J=K,H} \sum_{\iota=I,C} \omega_{J\iota\phi}(t)\Xi_{J\iota}(t)j\iota(t+1) \tag{13b}$$

$$\lim_{t\to\infty} E\left[\tilde{b}_H(t)\beta^t\right] \ge 0 \tag{13c}$$

$$(1+\sigma_{bHT}) \cdot \tilde{b}_{H0} \le E\left[\tilde{b}_H(T)\right] \le (1-\sigma_{bHT}) \cdot \tilde{b}_{H0} \tag{13d}$$

As with the notation of physical stocks J_ι, $B_H^-(t+1)$ and $B_H(t+1;\phi_{t+1})$ represent the stock level at the beginning of Period $t+1$, and the level after the-ϕ_{t+1}-scale disaster arrives, respectively. r is the interest rate. $GDP(t)$ is the gross domestic product. $Q_T(t), Q_{Tf}(t),$ and $Q_N(t)$ represent domestic households' consumption of domestic T-goods, foreign T-goods, and N-goods, respectively. $\tau(t)$ is a lump-sum tax per household. $\eta_{J_\iota}(t)$ is the per-household level of investment in stock $J\iota$. $j\iota(t)$ is the per-household level of stock $J\iota(t)$. The second term of the second line on the right-hand-side of Eq.(13a) identifies costs of investment in capital and household assets in both areas, where the second term in the square bracket represents the adjustment cost of investment, meaning that the second term does not result in an increase in stocks as is checked on Eq.(1a). The third line of the right-hand-side of Eq.(13a) represents payments of the insurance premium.

Equation (13b) indicates that insurance payouts are obtained after the occurrence of disaster, the amount of which is determined by the disaster scale ϕ. Inequality (13c) represents the No-Ponzi-Game (NPG) condition that is defined on the variable of the effective labor unit: $\tilde{b}_H(t) = B_H(t)/\{A(t)L(t)\}$. NPG condition means that debt will not grow too fast so that its growth rate must be smaller than the discount rate (interest rate) in the infinite future.

Inequality condition (13d), which goes beyond the NPG condition, is introduced into this model to evaluate rigorously the effect of policies at the end of the policy planning period T. This condition indicates that the expected level of the external assets, $E\left[\tilde{b}_H(T)\right]$, must stay within a certain range around its initial level, $\tilde{b}_{H0}$, (whose sign is negative in many cases). Without this condition, the policy evaluation in terms of GDP would be distorted by cases in which GDP is enhanced while a country is accumulating too much foreign debt to invest in production capital. Although the NPG condition also works for controlling the level of debts, it is not operational enough for the purpose of the policy evaluation of the model.

4.10. Household's utility

The dynamic optimization problem of the representative household (hereafter referred to as Household) is formulated to directly derive the aggregate demand functions. Inequality among households is not considered here. The single-period utility function of the representative household of the effective labor unit is represented as follows:

$$U\left(\tilde{q}_{TT}(t), \tilde{q}_N(t), \tilde{h}(t), \tilde{b}_H(t), \tilde{b}_G(t)\right)$$
$$= \frac{A}{1-\theta}\left\{(\tilde{q}_{TT}(t)^{\gamma_{TT}}\tilde{q}_N(t)^{\gamma_N})^{1-\theta} + \chi_H \tilde{h}(t)^{1-\theta}\right\} + Au_0 \cdot P_b\left(\tilde{b}_H, \tilde{b}_G, t\right) \tag{14}$$

where $\tilde{q}_{TT}(t) = Q_{TT}(t)/\{A(t)L(t)\}$ is T-good composite that is composed of domestic and foreign T-goods as formulated below in Eq.(15). $\tilde{q}_N(t) = Q_N(t)/\{A(t)L(t)\}$, and $\tilde{h}(t) = H(t)/\{A(t)L(t)\}$. $\tilde{b}_H(t)$ are Household's bonds, $\tilde{b}_G(t) = B_G(t)/\{A(t)L(t)\}$ are government bonds discussed in detail in section 4.12. The household receives utility by consuming T-good composites, N-goods, and household assets. $P_b(\cdot)$ is a penalty function of $\tilde{b}_H$ and $\tilde{b}_G$ that is tentatively introduced as the penalty to prevent too large debts represented by negative positions of household bonds, $\tilde{b}_H$, and government bonds, $\tilde{b}_G$. The impact of this function should be excluded by setting some parameters accordingly during calibration runs because of limited theoretical basis. The household is assumed to be risk averse. θ is a parameter representing the degree of relative risk aversion. γ_{TT} and γ_N are share parameters of sub-utility of non-durable goods, represented by the first term of the right-hand-side of Eq.(14). χ_H is a weight, representing relative strength of preference between non-durable goods and household asset. T-good composite is composed in the following way:

$$\tilde{q}_{TT}(t) = \left\{\gamma_T \tilde{q}_T(t)^{\gamma_{TT0}} + \gamma_{Tf}\left\{\tilde{q}_{Tf}(t) + \tilde{q}_{GTf}(t,\phi)\right\}^{\gamma_{TT0}}\right\}^{\frac{1}{\gamma_{TT0}}} \tag{15}$$

where $\tilde{q}_T(t) = Q_T(t)/\{A(t)L(t)\}$ represents T-goods, and $\tilde{q}_{Tf}(t) = Q_{Tf}(t)/\{A(t)L(t)\}$, foreign T-goods purchased by Household, $\tilde{q}_{GTf}(t,\phi)$, foreign T-good that Government purchases and provide to Household after the scale-ϕ-disaster as disaster relief good. $\gamma_T, \gamma_{Tf}, \gamma_{TT0}$ are parameters that form the constant-elasticity-of-substitution (CES) function applied to compose T-good composite.

Household takes $\tilde{q}_{GTf}(t,\phi)$ and the market prices as given, and determines the optimal combination of $\tilde{q}_T(t)$ and $\tilde{q}_{Tf}(t)$, so that it minimizes expenditure of having $\tilde{q}_{TT}(t)$ every period in the following problem:

$$p_T(t)\tilde{q}_T(t) + p_{Tf}\left\{\tilde{q}_{Tf}(t) + \tilde{q}_{GTf}(t,\phi)\right\} \tag{16a}$$

$$subject\ to\ \left\{\gamma_T \tilde{q}_T(t)^{\gamma_{TT0}} + \gamma_{Tf}\left\{\tilde{q}_{Tf}(t) + \tilde{q}_{GTf}(t,\phi)\right\}^{\gamma_{TT0}}\right\}^{\frac{1}{\gamma_{TT0}}} = \tilde{q}_{TT}(t) \tag{16b}$$

The optimal $\tilde{q}_T(t)$ and $\tilde{q}_{Tf}(t)$ are introduced as functions of $\tilde{q}_{TT}(t)$ as well as $\tilde{q}_{GTf}(t,\phi), p_T(t)$ and p_{Tf} as follows:

$$\tilde{q}_T(t) = \lambda_T(t)\tilde{q}_{TT}(t) \tag{17a}$$

$$\tilde{q}_{Tf}(t) = \lambda_{Tf}(t)\tilde{q}_{TT}(t) - \tilde{q}_{GTf}(t,\phi) \tag{17b}$$

$$where\ \ \lambda_T(t) = \left(\frac{\gamma_T}{p_T(t)}\lambda_{TT}(t)\right)^{\frac{1}{1-\gamma_{TT0}}} \tag{17c}$$

$$\lambda_{Tf}(t) := \left(\frac{\gamma_{Tf}}{p_{Tf}(t)}\lambda_{TT}(t)\right)^{\frac{1}{1-\gamma_{TT0}}} \tag{17d}$$

$$\lambda_{TT}(t) = \left\{\left(\frac{\gamma_T}{p_T(t)^{\gamma_{TT0}}}\right)^{\frac{1}{1-\gamma_{TT}}} + \left(\frac{\gamma_{Tf}}{p_{Tf}^{\gamma_{TT}}}\right)^{\frac{1}{1-\gamma_{TT0}}}\right\}^{-\frac{1-\gamma_{TT0}}{\gamma_{TT0}}} \tag{17e}$$

The level of $\tilde{q}_{TT}(t)$ is determined in the dynamic stochastic optimization problem; Household finally maximizes the following expected lifetime utility:

$$E\left[\sum_{t=0}^{\infty} \quad U(\cdot)\left(\frac{1+\zeta_L}{1+r}\right)^t\right] \tag{18}$$

The utility maximization of the representative household is the main problem of the model. Here the optimal controls for the stock formations under risks of disaster and environmental change are included in the expected household utility. The framework of the main problem is shown in detail in subsequent sections.

4.11. Foreign visitors' demand

In this application of DYNAMMICs, tourism-related demand contributes to a large share of total demand for products of the country and therefore is a special focus. For other countries, even if the impact of tourism is not as large as that of the Caribbean countries, demand of foreign visitors that also includes businesspersons is not negligible in domestic markets. They enjoy Non-traded goods, namely local services, culture, and nature they cannot consume by staying in their country. Additionally, they consume (domestic) T-goods during their stay. On the other hand, their concern over stock formations for development of the country would be little. For that reason, the foreign visitors' consumption problem is formulated as a static problem that does not incorporate a decision on investment or other dynamic controls. An objective function of the problem reflects the purpose of foreigners' visits, and therefore, differs among target countries. From their optimization problems, functions of foreign visitors' demand for domestic T-good $\tilde{q}_{FT}^{*}(\cdot)$, N-good $\tilde{q}_{FN}^{*}(\cdot)$, and the number of foreign visitors $n_F^{*}(\cdot)$ are derived from an equilibrium condition.

4.12. Government policy

4.12.1. Expenditure

The central government (hereafter referred to as Government) develops and/or maintains stocks that are characterized as public goods, these are infrastructure for production $G\iota$, a part of land $\upsilon_{GZ\iota}Z_\iota$ $(0 \leq \upsilon_{GZ\iota} \leq 1)$, a part of natural asset $\upsilon_{GN\iota}N_\iota$ $(0 \leq \upsilon_{GN\iota} \leq 1)$, and disaster risk reduction (DRR) stocks D_ι, where $\iota = I, C$, and $\upsilon_{GZ\iota}$, $\upsilon_{GN\iota}$ $(0 \leq \upsilon_{GZ\iota}, \upsilon_{GN\iota} \leq 1)$ are parameters indicating percentages of government's ownership. DRR stock is composed of built (non-nature-based) facilities for disaster mitigation such as stock of off-shore break water, seawall, revetment, groyne, etc. Moreover, government provides disaster relief goods to households after severe disasters, equivalent to government's compensation in terms of private goods, by procuring foreign T-goods on international markets. Government's expenditure in Period t, $\Upsilon(t)$, is composed in the following way:

$$\Upsilon(t) = p_\eta(t)L(t)\sum_{\iota=I,C} \eta_{G\iota}(t)\left\{1 + \Gamma_{G\iota 0}\cdot\left(\sum_{i=T,N,Tf} (\alpha_{\eta i})^2\right)\cdot\left(\frac{p_\eta(t)\eta_{G\iota}(t)}{g_\iota(t)}\right)\right\}$$

$$+p_\eta(t)L(t)\sum_{J=Z,N,D}\sum_{\iota=I,C} \underline{p}_{\eta J\iota}\eta_{J\iota}(t) + p_{Tf}Q_{GTf}(t,\phi) \qquad (19a)$$

$$where\ \ Q_{GTf}(t,\phi) = A(t)L(t)\cdot\tilde{q}_{GTf}(t,\phi) \qquad (19b)$$

$$\tilde{q}_{GTf}(t,\phi) = \tilde{q}_{GTf0}(LR_l)\cdot\left(1+\zeta_{qGTf}\right)^t \quad (for\ \ l = 1,2,3,4) \qquad (19c)$$

The first line on the right-hand-side of Eq.(19a) represents costs for investment/maintenance/ reconstruction in infrastructure for production. The first term of the second line indicates costs for land, natural asset, and DRR stock. The third term of the second line is expenditure for disaster relief goods. Eqs.(19b) and (19c) illustrate one example of the disaster-relief-good policy, where the amounts are linked to the loss ranges, LR_l $(l = 1,2,3,4)$, of the risk layering approach explained in section 4.12.3.

4.12.2. Finance

Government finances the above expenditures by controlling two-dimensional financial stocks: bond $B_G(t)$ and liquidity $M(t)$. All expenditure is assumed to be mediated by the reserved liquidity, implying that Government is faced with a "cash-in-advance constraint". The formation process of the liquidity reserve and the expenditure constraint are given as follows:

$$M^{-}(t+1) = (1+r_M)M(t) - \Upsilon(t) + \Theta_1(t) \tag{20a}$$

$$M(t) = M^{-}(t) + \sum_{l=2,3,4} \Pi_{dl}(t, \phi_t) \tag{20b}$$

$$\Upsilon(t) \leq (1+r_M)M(t) \tag{20c}$$

r_M is interest rate of liquidity that is a parameter of a small value, $0 \leq r_M \leq r$. $\Theta_1(t)$ (≥ 0) is transfer from Government bond $B_G(t)$ to the liquidity reserve. Moreover, $\Pi_{d2}, \Pi_{d3}, \Pi_{d4}$ are liquidity supplies by means of the contingent credit, the insurance, and the high-layer insurance, respectively. They are provided based on special contracts with foreign financial institutions, discussed in depth in the following sections. These contracts supply urgent supplies of liquidity $\{\Pi_{dl}(t, \phi_t) | l = 2,3,4\}$ and are implemented to be spent within that period t as shown by Eqs.(20b)-(20c). Note that, with $\Theta_1(t) \geq 0$ and the inequality (20c), $M^{-}(t+1) \geq 0$ holds for any period t.

The level of Government's holdings of foreign bonds in international financial markets changes in the following way:

$$B_G{}^{-}(t+1) = (1+r)B_G(t) + L(t)\tau(t) - \sum_{l=1,\cdots,4} \Theta_l(t) \tag{21a}$$

$$B_G(t) = B_G{}^{-}(t) - \Pi_{d2}(t, \phi_t) \tag{21b}$$

$$\lim_{t\to\infty} E\left[\tilde{b}_G(t)\beta^t\right] \geq 0 \tag{21c}$$

$$(1+\sigma_{bGT}) \cdot \tilde{b}_{G0} \leq E\left[\tilde{b}_G(T)\right] \leq (1-\sigma_{bGT}) \cdot \tilde{b}_{G0} \tag{21d}$$

where $L(t)\tau(t)$ is tax income, and $\{\Theta_l(t) | l = 1, \cdots, 4\}$ is payment for preparedness with financial vehicles: transfer to the liquidity reserve $(l = 1)$, payments of premiums for the contingent credit $(l = 2)$, the insurance $(l = 3)$, and the high-layer insurance $(l = 4)$. Equation (21b) means that, due to the liquidity supply $\Pi_{d2}(t, \phi_t)$ based on the contingent credit contract, the level of the bond $B_G(t)$ drops by $\Pi_{d2}(t, \phi_t)$ of the current (Period-t) value, which is supposed to be returned by divided payments later over multiple periods. Inequality (21c) represents No-Ponzi-Game (NPG) condition that is imposed on the variable in terms of effective labor units: $\tilde{b}_G(t) = B_G(t)/\{A(t)L(t)\}$, and implies that the position of $B_G(t)$ can be temporally negative unlike the liquidity reserve $M(t)$. In line with textbook NPG definition (e.g. Barro and Sala-i-Martin, 2004, p. 89) the condition restricts the amount of borrowing possible by requiring a non-negative expected value of weighted government borrowing. This condition is needed so that government consumption cannot become infinite given a situation where governments increasingly borrow to finance consumption and credit repayment given the infinite time horizon of the model. Inequality condition (21d) is incorporated with the same intention as the condition (13d), namely the limitation of debt.

The reason for requiring such a two-dimensional formulation is that without $M(t)$, the contingent credit contract would not be feasible because realistically governments can take up debt and apply long-term management. This could lead to the conclusion that pre-disaster contract (especially with extra fee) is not needed. This logic also applies to the need for insurance; as long as policy effects are evaluated in terms of "expected growth" (because it is not appropriate to discuss a specific series of disaster occurrences), the larger magnitude of insurance premium than the expected payment of insurance money suggests that insurance is inefficient or wasteful. To avoid such misleading conclusions, it is assumed that one period of time is needed to transfer resources from $B_G(t)$ to $M(t)$, such that prompt recovery policy at disaster time becomes possible via large $M(t)$ at that period. On the other hand, due to low profitability of investment in $M(t)$ (because of lower interest rate), it is not an efficient strategy to keep too large $M(t)$ all the time. In summary, there exists a conflict and thus trade-off between the stocks, $M(t)$ and $B_G(t)$. However, by applying such financial contracts, governments can keep high $B_G(t)$ to obtain large interest (more generally, to benefit by various financial operations omitted in our model) while preparing for the uncertain need for prompt expenditure after disaster. The two-dimensional formulation is a technical device of modelling to illustrate such a benefit of the pre-disaster financial contracts.

4.12.3. Risk layering strategy

A main concern of the model is the "risk layering strategy", where usage of each measure is limited to avoid over excessive claims from each financial institution. The layers are assumed to be designed on the total disaster damage (also referred to in this model as direct losses – please see Palekiene et al. 2014) per effective labor that are suffered by Government.

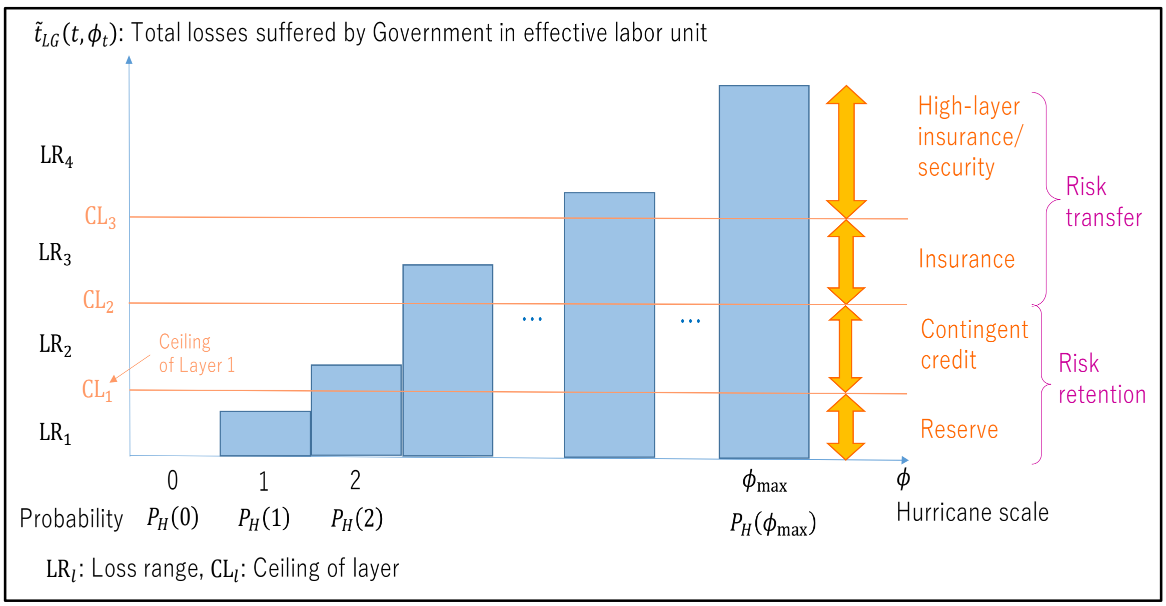

Figure 7. Risk layer and financial measures.

The total damage to Government's stocks caused by disaster of the scale ϕ_t in Period t, $TLG(t,\phi_t)$, and those per effective labor, $\tilde{t}_{LG}(t,\phi_t)$, are given as follows:

$$TLG(t,\phi_t) = p_\eta(t) \sum_{\iota=I,C} \omega_{G\iota\phi} G_\iota^-(t) + p_\eta(t) \sum_{J=Z,N} \sum_{\iota=I,C} \omega_{J\iota\phi} \upsilon_{GJ\iota} A(t)L(t)J_\iota^-(t) \quad (22a)$$

$$\begin{aligned} \tilde{t}_{LG}(t,\phi_t) &= \frac{TLG(t,\phi_t)}{A(t)L(t)} \\ &= p_\eta(t) \sum_{\iota=I,C} \omega_{G\iota\phi} \tilde{g}_\iota^-(t) + p_\eta(t) \sum_{J=Z,N} \sum_{\iota=I,C} \omega_{J\iota\phi} \upsilon_{GJ\iota} J_\iota^-(t) \end{aligned} \quad (22b)$$

Figure 7 illustrates the disaster scales, the total damages, the layers, and the financial measures. $CL_l(l = 1, 2, 3)$ represents the ceiling of the lth layer, and LR_l, the damage range defined by $(CL_{l-1}, CL_l]$. Although relations between the scale-ϕ-damage and the range are not always like those in Figure 7 because they depend on mitigation policies and other factors, the relations between the layers and the financial measures are defined as in the illustration. These damages of Layer 1, Layer 2, Layer 3, and Layer 4 and are covered by the liquidity reserve, the contingent credit, the insurance, and the high-layer insurance, respectively.

If the total Government damages per effective labor are within Layer 1, namely $\tilde{t}_{LG}(t,\phi_t) \in LR_1$, no liquidity supply is given by outside financial institution.

If $\tilde{t}_{LG}(t,\phi_t)$ is increased to be included in Layer 2, the contingent credit is applied. Contingent credit is an emergency loan contract, meaning that a borrower is required to repay the loan. In the present case illustrated by Figure 8, Government concludes a contract with a bank by paying the contract fee $\tilde{\theta}_2$ every period. If disaster of the scale ϕ_{td} occurs in Period t_d, the following amount of liquidity, $\tilde{\pi}_{d2}(t_d, \phi_{td})$ per effective labor is supplied by the bank:

$$\tilde{\pi}_{d2}(t_d, \phi_{td}) = \begin{cases} 0 & if \quad \tilde{t}_{LG}(t_d,\phi_{td}) \in LR_1 \\ \tilde{t}_{LG}(t_d, \phi_{td}) - CL_1 & if \quad \tilde{t}_{LG}(t_d,\phi_{td}) \in LR_2 \\ CL_2 - CL_1 & if \quad \tilde{t}_{LG}(t_d,\phi_{td}) \in \{ LR_3 \cup LR_4 \} \end{cases} \quad (23)$$

Then, Government starts the repayment in Period $t_d + T_{C1}$, where T_{C1} is called "the length of grace period" and ends it in Period $t_d + T_{C1} + T_{C2} - 1$, where T_{C2} is the length of the repayment period. Assuming the repayment amount is constant over time, and the interest rate for this contract is given by r_C, the following equation holds:

$$\tilde{\pi}_{d2}(t_d,\phi_{td}) = \tilde{\theta}_{Rd2}(t_d,\phi_{td}) \sum_{t\prime=T_{C1}}^{T_{C1}+T_{C2}-1} \left(\frac{1}{1+r_C}\right)^{t\prime} \quad (24)$$

which determines the per-period repayment amount as follows:

$$\tilde{\theta}_{Rd2}(t_d,\phi_{td}) = \frac{\tilde{\pi}_{d2}(t_d, \phi_{td})}{R_c} \quad (25a)$$

$$where \quad R_C = \sum_{t\prime=T_{C1}}^{T_{C1}+T_{C2}-1} \left(\frac{1}{1+r_C}\right)^{t\prime} \quad (25b)$$

In Layers 3 and 4, Government obtains liquidity through insurance money. The liquidity provided in Layer 3 is termed "(Basic) Insurance", and the one covered in Layer 4 is termed "High-layer insurance". Insurance money for Layer 3, $\tilde{\pi}_{d3}(t_d,\ \phi_{td})$, is determined in the following way:

$$\tilde{\pi}_{d3}(t_d,\ \phi_{td}) = \begin{cases} 0 & if \quad \tilde{t}_{LG}(t_d, \phi_{td}) \in \{ LR_1\ \cup LR_2 \} \\ \tilde{t}_{LG}(t_d,\ \phi_{td}) - CL_2 & if \quad \tilde{t}_{LG}(t_d, \phi_{td}) \in LR_3 \\ CL_3 - CL_2 & if \quad \tilde{t}_{LG}(t_d, \phi_{td}) \in LR_4 \end{cases} \tag{26}$$

Insurance premium, $\tilde{\theta}_3(t_d)$, is determined by:

$$\tilde{\theta}_3(t_d) = \xi_{0G3}\left[\iint_{\tilde{t}_{LG}(t_d,\ \phi_{td})\in LR_3} \{\tilde{t}_{LG}(t_d,\ \phi_{td}) - CL_2\} dProb(\tilde{t}_{LG}) + \{CL_3 - CL_2\} P_{\tilde{t}LG}(4{:}\,s)\right] \tag{27}$$

where $dProb(\tilde{t}_{LG})$ is the probability density of the total damages $\tilde{t}_{LG}$, and $P_{\tilde{t}LG}(4{:}\,s)$ is the probability of $\tilde{t}_{LG}(t_d, \phi_{td}) \in LR_4$ given the state s. Therefore, the square bracket is equivalent to the expected amount of payment of the insurance money on Layer 3. ξ_{0G3} is the mark-up rate similar to the one of Household insurance.

Likewise, high-layer insurance contract is defined by insurance money, $\tilde{\pi}_{d4}(t_d,\ \phi_{td})$, and premium, $\tilde{\theta}_4(t_d)$, determined in the following way:

$$\tilde{\pi}_{d4}(t_d,\ \phi_{td}) = \begin{cases} 0 & if \quad \tilde{t}_{LG}(t_d, \phi_{td}) \in \{ LR_1\ \cup LR_2 \cup LR_3 \} \\ \tilde{t}_{LG}(t_d,\ \phi_{td}) - CL_3 & if \quad \tilde{t}_{LG}(t_d, \phi_{td}) \in LR_4. \end{cases} \tag{28a}$$

$$\tilde{\theta}_4(t) = \xi_{0G4}\left[\iint_{\tilde{t}_{LG}(t_d,\ \phi_{td})\in LR_4} \{\tilde{t}_{LG}(t_d,\ \phi_{td}) - CL_3\} dProb(\tilde{t}_{LG})\right] \tag{28b}$$

ξ_{0G4} is the mark-up rate given to Layer 4. Note that, unlike the contingent credit, Government must pay the insurance premiums for the two layers every period t by the amounts, $\tilde{\theta}_3(t)$ and $\tilde{\theta}_4(t)$, damages in that period, while Government does not have to repay the insurance claims after disbursement.

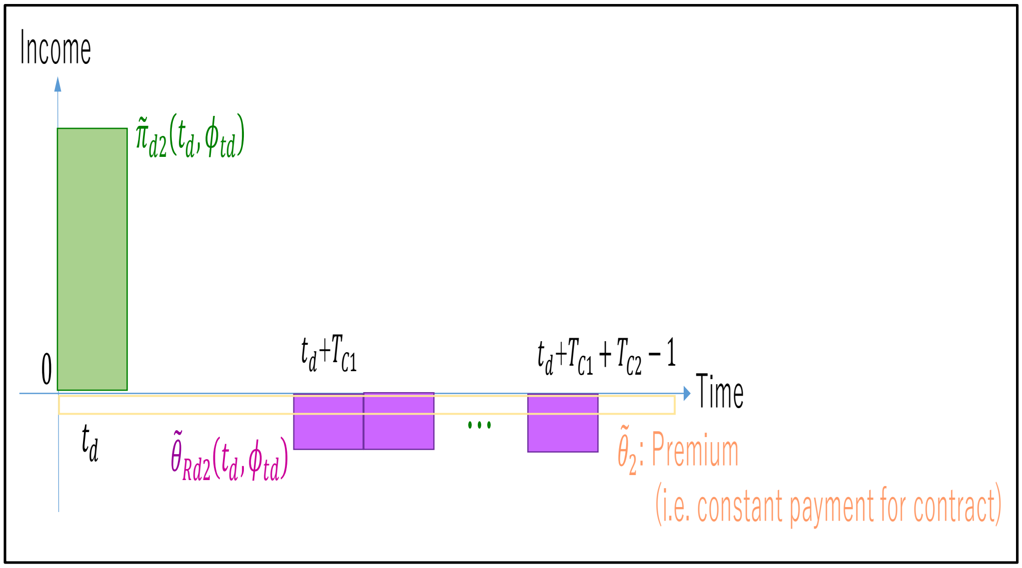

Figure 8. Contingent credit system.

4.13. Market clearing conditions, GDP, and trade balance

Four of the markets included in the model are closed. Closed markets are markets for domestic T-good, N-good, labor, and capital. Market clearing conditions for domestic T-good and N-good are given respectively by the following equations:

$$\begin{aligned} Y_T(t) &= \kappa_{TT} Y_T(t) + \kappa_{TN} Y_N(t) + Q_T(t) + n_F(t) Q_{FT}(t) + D_{FT}\big(p_T(t)\big) \\ &+ L(t) \sum_{J=K,H,G} \sum_{\iota=I,C} \eta_{J\iota T}(t) \left\{ 1 + \Gamma_{J\iota} \cdot \left(\frac{p_T(t)\eta_{J\iota T}(t)}{j_\iota(t)} \right) \right\} \\ &+ L(t) \sum_{J=Z,N,D} \sum_{\iota=I,C} \underline{p}_{\eta J\iota} \eta_{J\iota T}(t) \end{aligned} \tag{29a}$$

$$\begin{aligned} Y_N(t) &= \kappa_{NT} Y_T(t) + \kappa_{NN} Y_N(t) + Q_N(t) + n_F(t) Q_{FN}(t) \\ &+ L(t) \sum_{J=K,H,G} \sum_{\iota=I,C} \eta_{J\iota N}(t) \left\{ 1 + \Gamma_{J\iota} \cdot \left(\frac{p_N(t)\eta_{J\iota N}(t)}{j_\iota(t)} \right) \right\} \\ &+ L(t) \sum_{J=Z,N,D} \sum_{\iota=I,C} \underline{p}_{\eta J\iota} \eta_{J\iota N}(t) \end{aligned} \tag{29b}$$

where $D_{FT}\big(p_T(t)\big)$ represents the export of domestic T goods, that is, a demand function for domestic T goods outside of the country. Its form is assumed as follows:

$$D_{FT}\big(p_T(t)\big) = A(t)L(t)d_{TF0} \cdot exp\{-d_{TF1} \cdot p_T(t)\} \tag{30}$$

where d_{TF} and d_{TF1} are parameters of positive values. The left-hand-sides of Eqs. (29a) and (29b) represent supplies of T-good and N-good, respectively, while the right-hand-sides

represent demands. The first and second terms of the right-hand-sides of Eqs. (29a) and (29b) are intermediate demands. The other terms on the right-hand-sides represent consumption. The terms on the second lines are demands for investments.
Market clearing conditions for labor and capital are given by the following equations:

$$L_T(t) + L_N(t) = L(t) \tag{31a}$$
$$K_T(t) + K_N(t) = K(t) = K_I(t) + K_C(t) \tag{31b}$$

The left-hand-sides of both equations above represent demands for domestic T-good and N-good sectors. $K_I(t)$ and $K_C(t)$ on the right-hand-side of Eq.(31b) show spatial distribution of capital $K(t)$.

Gross domestic product (GDP) is accumulated as follows:

$$GDP(t) = p_{vT}(t)Y_T(t) + p_{vN}(t)Y_N(t) \tag{32a}$$
$$where\ \ p_{vT}(t) = p_T(t) - \kappa_{TT} \cdot p_T(t) - \kappa_{NT} \cdot p_N(t) - \kappa_{TfT} \cdot p_{Tf} \tag{32b}$$
$$p_{vN}(t) = p_N(t) - \kappa_{TN} \cdot p_T(t) - \kappa_{NN} \cdot p_N(t) - \kappa_{TfN} \cdot p_{Tf} \tag{32c}$$

$p_{vT}(t)$ and $p_{vN}(t)$ are the value-added prices of T-good and N-good sectors, respectively.
The trade balance condition of the macroeconomy is derived by Eqs. (13a), (20a), (21a), (29a), (29b) and (32a), as follows:

$$\begin{aligned}
&B_H^-(t+1) + B_G^-(t+1) + M^-(t+1) \\
&= (1+r)\{B_H(t) + B_G(t)\} + (1+r_M)M(t) + p_T(t)\{n_F(t)Q_{FT}(t) + D_{FT}(p_T(t))\} \\
&+p_N(t)n_F(t)Q_{FN}(t) - p_{Tf}[k_{TfT}Y_T(t) + k_{TfN}Y_N(t) + Q_{Tf}(t) + Q_{GTf}(t) \\
&+L(t)\sum_{J=K,H,G}\ \sum_{\iota=I,C} \eta_{J\iota Tf}(t)\left\{1 + \Gamma_{J\iota 0}\cdot\left(\frac{p_{Tf}\cdot\eta_{J\iota Tf}(t)}{j_\iota(t)}\right)\right\} \\
&+ L(t)\sum_{J=Z,N,D}\ \sum_{\iota=I,C} \underline{p}_{\eta J\iota}\eta_{J\iota Tf}(t)\ \ ] \\
&-p_\eta(t)\sum_{J=K,H}\ \sum_{\iota=I,C} \zeta_{J\iota}\Xi_{J\iota}(t)J_\iota(t+1) - \sum_{l=2,3,4} \Theta_l(t)
\end{aligned} \tag{33}$$

4.14. Dynamic optimization

4.14.1. State and control variables

The above equations are detrended to formulate the dynamic optimization problem, so that state variables do not diverge to infinity. Detrending is executed by dividing equations either by $\{A(t)L(t)\}$, $A(t)$ or $L(t)$. As a result, most endogenous variables are turned into their counterparts represented in effective labor units denoted by $\tilde{x}(t)$. With the framework using detrended variables $\tilde{x}(t)$, even if $\tilde{x}(t)$ reaches steady state $\tilde{x}^{SS}$ where its value does not further increase, its original-unit variable, $X(t)$, will keep growing at rate $X(t) = A(t)L(t)\tilde{x}^{SS}$ because $A(t)$ and $L(t)$ continuously grow. For simplicity and readability, the detrending of variables is discussed in this general form and not explicitly for each detrended variable.

In the dynamic optimization model, variables are categorized into state variables s (vector), decision (control) variables d, and parameters. Further, state variables are categorized into exogenous state variables s^X and endogenous state variables s^N, namely $s = (s^X, s^N)$. The former variables change over time but are not affected by choices of decision variables, while the latter are controlled by decision variables as well as affected by other factors including random variables. Moreover, the model includes a category for price $p = (p_T, p_N)$ independent of state variables (although they may be interpreted as "intra-temporal state variable").

In the full-scale simulation model, the exogenous state variables, s^X, and the endogenous state variables, s^N, are given respectively by:

$$s^X = (t, \phi_t, \varepsilon_{ZCt}, \varepsilon_{NCt}, \varepsilon_t), \tag{34a}$$

$$s^N = (\tilde{k}_I, \tilde{k}_C, \tilde{h}_I, \tilde{h}_C, Z_C, N_C, \tilde{g}_I, \tilde{g}_C, \tilde{b}_H, \tilde{b}_G, \widetilde{m}) \tag{34b}$$

The decision-variable vector d is composed of:

$$d = (\tilde{q}_{TT}, \tilde{q}_T, \tilde{q}_{Tf}, \tilde{q}_N, l_T, l_N, \tilde{k}_T, \tilde{k}_N, \tilde{\eta}_{KI}, \tilde{\eta}_{KC}, \tilde{\eta}_{HI}, \tilde{\eta}_{HC}, \tilde{\eta}_{GI}, \tilde{\eta}_{GC}, \tilde{q}_{FT}, \tilde{q}_{FN}, \tilde{q}_{FTf}, n_F, \tilde{d}_{FT}) \tag{35}$$

This problem is subject to the "Curse of dimensionality.[11] It limits the possibility of computation of problems with large dimensions of state variables. Several measures are taken to cope with this problem. First, "schedules" are given to some decision variables in an "a-priori way". For example, we assume that the level of investment in DRR stock, $\tilde{\eta}_{D\iota}(t)$ $(\iota = I, C)$, follows the schedule given by $\tilde{\eta}_{D\iota}(t) = \tilde{\eta}_{D\iota} \cdot (1 + \zeta_{D\iota})^t$ where $\tilde{\eta}_{D\iota 0}$ and $\zeta_{D\iota}$ are policy parameters. In this case, $\tilde{\eta}_{D\iota}(t)$ is linked only to t and not influenced by other state variables in Period t. This is not an ideal modeling approach because such decisions disregard occurrence of contingency including disasters, and hence are not consistent with "dynamic stochastic optimization". On the other hand, by applying such "scheduled (pre-determined) controls" of decision variables and "scheduled developments" of state variables, those variables can be excluded from the state space and absorbed into $t \in s^X$ (in state-space-wise) as shown in Eq.(34a). Second, while a supercomputer will face a challenge to deal with the dimensions implied by a full-scale simulation model shown in Eqs. (34a), (34b) and (35), the PC version of the model is developed where the dimensions are reduced by applying the scheduled (pre-determined) controls/developments to some more variables.

4.14.2. Event sequence

It is crucially important to identify an order of events in dynamic stochastic optimization problems because such an order determines availability of information for each decision. For example, decisions on the investment level differ between a situation where disaster may occur probabilistically and one where disaster has just occurred.

As mentioned above, decision rules for a selection of variables are determined at the beginning. Variables for which this is the case are the scheduled (pre-determined) controls/developments. All other decisions are made every period t in the following sequence, and as illustrated in Figure 9:

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[11] "Curse of dimensionality" is a term coined by applied mathematician, Richard E. Bellman, who introduced dynamic programming in Bellman (1957). It refers to the problem caused by the exponential increase in volume associated with adding additional dimensions to a mathematical space.

1. At the beginning of Period t, the levels of stock variables before the occurrence of the shocks, $s^{N-}(t)$, are confirmed.
2. The shocks arrive; values of the random variables such as the disaster scale ϕ_t, the environmental change $\varepsilon_{ZC\,t}$, etc., are determined. Accordingly, payments of claims of insurance and the layered contract are implemented, resulting in determination of the post-shock state variables in Period t, $s^N(t)$.
3. Having a set of the state variables $s(t) = (s^X(t), s^N(t))$, the Bellman equation (the main policy equation in dynamic programming (Bellman, 1957)) of Period t is identified; namely, the optimization problem is set.
4. Decisions are made. The levels of production, consumption, investment, etc., are determined as well as the market prices. The set of optimal controls, $d^*(s(t))$, is derived. The level of one-period utility, $u(t)$, is obtained.
5. At the end of Period t, some stocks are depreciated, while others are recovered from disaster damage without cost. The stock variables are updated to $s^{N-}(\mathrm{s(t)}, d^*(s(t))) = s^{N-}(t+1)$. Time moves to the next period $t+1$, and the same cycle is repeated.

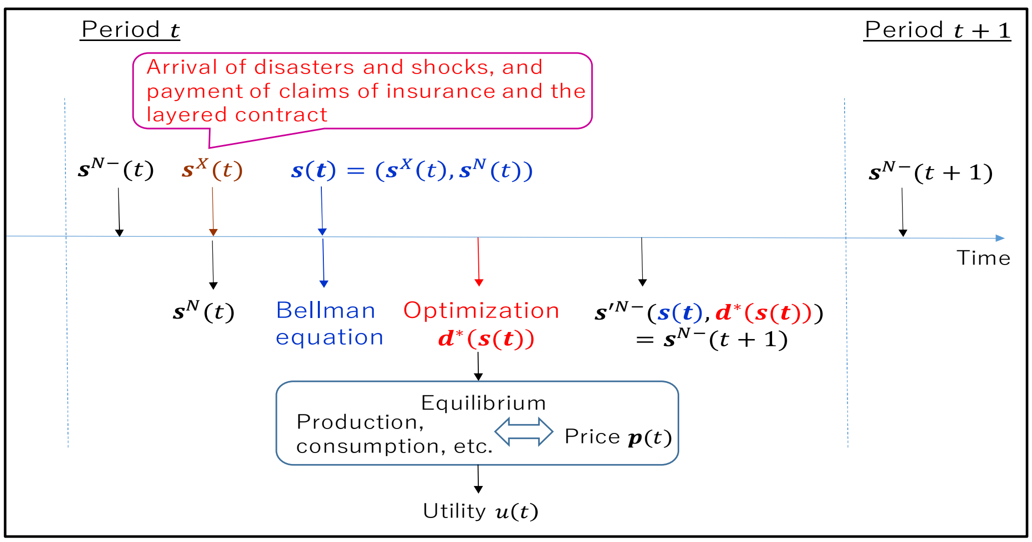

Figure 9. Event sequence.

4.14.3. Value function and Bellman equation

The objective function of the dynamic stochastic optimization problem is transformed as follows:

$$E\left[\sum_{t=0}^{\infty} U(\cdot)\left(\frac{1+\zeta_L}{1+r}\right)^t\right] = E\left[\sum_{t=0}^{\infty} u(\cdot)\left\{\frac{(1+\zeta_A)(1+\zeta_L)}{1+r}\right\}^t\right] = E\left[\sum_{t=0}^{\infty} \beta^t u(\cdot)\right] \quad (36a)$$

$$where\ u(\cdot) = \frac{U(\cdot)}{(1+\zeta_A)^t} \quad (36b)$$

$$\beta = \frac{(1+\zeta_A)(1+\zeta_L)}{1+r} \quad (36c)$$

$u(\cdot)$ is the one-period utility, and β $(0 < \beta < 1)$ is the discount factor in the detrended framework. The value function, $V(s)$, is defined by the maximized objective function, and meets the recursive structure called the Bellman equation as follows:

$$V(s) = E\left[\sum_{t=0}^{\infty} \beta^t u(\cdot)\right] = \left[u(\cdot) + \beta E\left[V\left(s'(s,d)\right)\right]\right] \tag{37}$$

where s' represents a state in the next period, that is dependent on the current state, s, and the control, d. To repeat the above-mentioned logic, the value function, $V(s)$, is the maximum expected lifetime utility achievable by the optimal decision under the state s, $d^*(s)$, which derives the optimal state in the next period $s'^* = s'\left(s,\ d^*(s)\right)$. Hence the dynamic stochastic optimization is specified so that the Bellman equation (37) is solved with the constraint conditions, the transition equations, and the equilibrium conditions.

4.15. Policy indicators

The Bellman equation is solved numerically for the purpose of obtaining the decision rule under each state s, $d^*(s)$. In the next step, a Monte-Carlo simulation is carried out to investigate the effects of policies on the expected growth of the country.

The policy parameters, represented by the vector g, are categorized into two groups: $g = (g_{MI}, g_{PR})$ where g_{MI} includes policy parameters for disaster mitigation, and g_{PR}, those for two sectors.

The effect of a target policy, g, is measured by increase of the expected GDP from the level under the reference policy, $g_0 = (g_{MI0}, g_{PR0})$; namely by Total growth effect (TGE) defined by:

$$TGE(g,t) = MP(g,t) - MP(g_0,t) \tag{38}$$

Where $MP(g,t)$ represents the mean path of Monte-Carlo simulation obtained by:

$$MP(g,t) = E_\chi[SP^\chi(g,t)], \tag{39a}$$

$$where\ \ SP^\chi(g,t) = NDP(g,t) - \sum_{t' \le t} \widehat{D}^\chi(t', \phi_{t'}, g) \tag{39b}$$

$SP^\chi(g,t)$ represents the GDP path of the χ-th run of the simulation, that is approximately equal to No-disaster path, $NDP(g,t)$, minus the sum of decreases of GDP at disaster times t' up to t, $\widehat{D}^\chi\left(t', \phi_{t'}, g\right)$.

The Total growth effect (TGE) is composed of Disaster Risk Reduction Effect (DRRE) and Co-benefit production expansion effect (CPEE), two cases of decomposition depending on the order of changing g_{MI} and g_{PR}. The first case is given by:

$$TGE(g,t) = MP(g_{MI}, g_{PR}, t) - MP(g_{MI0}, g_{PR0}, t)$$
$$= \{MP(g_{MI}, g_{PR}, t) - MP(g_{MI0}, g_{PR}, t)\} + \{MP(g_{MI0}, g_{PR}, t) - MP(g_{MI0}, g_{PR0}, t)\}$$

$$= DRRE_1(g,t) + CPEE_1(g,t) \tag{40a}$$

$$where \;\; DRRE_1(g,t) = MP(g_{MI}, g_{PR}, t) - MP(g_{MI0}, g_{PR}, t) \tag{40b}$$

$$CPEE_1(g,t) = MP(g_{MI0}, g_{PR}, t) - MP(g_{MI0}, g_{PR0}, t) \tag{40c}$$

Moreover, DRRE is further decomposed into an ex-post damage mitigation effect (PDME) and an ex-ante risk reduction effect (ARRE):

$$\begin{aligned} DRRE_1(g,t) &= MP(g_{MI}, g_{PR}, t) - MP(g_{MI0}, g_{PR}, t) \\ &= NDP(g_{MI}, g_{PR}, t) - NDP(g_{MI0}, g_{PR}, t) \\ &+E_\chi\left[\sum_{t' \le t} \left\{\widehat{D}^\chi(t', \phi_{t'}, g_{MI0}, g_{PR}) - \widehat{D}^\chi(t', \phi_{t'}, g_{MI}, g_{PR})\right\}\right] \\ &= ARRE_1(g,t) + PDME_1(g,t), \end{aligned} \tag{41a}$$

$$where \;\; ARRE_1(g,t) = NDP(g_{MI}, g_{PR}, t) - NDP(g_{MI0}, g_{PR}, t) \tag{41b}$$

$$PDME_1(g,t) = E_\chi\left[\sum_{t' \le t} \left\{\widehat{D}^\chi(t', \phi_{t'}, g_{MI0}, g_{PR}) - \widehat{D}^\chi(t', \phi_{t'}, g_{MI}, g_{PR})\right\}\right] \tag{41c}$$

In other words, PDME is measured by the mean of actual damage reduction obtained at disaster times, while ARRE is given by the gap of the No-disaster paths.

Likewise, the second case of the decomposition results in:

$$\begin{aligned} TGE(g,t) &= MP(g_{MI}, g_{PR}, t) - MP(g_{MI0}, g_{PR0}, t) \\ &= \{MP(g_{MI}, g_{PR}, t) - MP(g_{MI}, g_{PR0}, t)\} + \{MP(g_{MI}, g_{PR0}, t) - MP(g_{MI0}, g_{PR0}, t)\} \\ &= DRRE_2(g,t) + CPEE_2(g,t), \end{aligned} \tag{42a}$$

$$where \;\; DRRE_2(g,t) = MP(g_{MI}, g_{PR}, t) - MP(g_{MI}, g_{PR0}, t) \tag{42b}$$

$$CPEE_2(g,t) = MP(g_{MI}, g_{PR0}, t) - MP(g_{MI0}, g_{PR0}, t) \tag{42c}$$

Moreover,

$$\begin{aligned} DRRE_2(g,t) &= MP(g_{MI}, g_{PR0}, t) - MP(g_{MI0}, g_{PR0}, t) \\ &= NDP(g_{MI}, g_{PR0}, t) - NDP(g_{MI0}, g_{PR0}, t) \\ &+E_\chi\left[\sum_{t' \le t} \left\{\widehat{D}^\chi(t', \phi_{t'}, g_{MI0}, g_{PR0}) - \widehat{D}^\chi(t', \phi_{t'}, g_{MI}, g_{PR0})\right\}\right] \\ &= ARRE_2(g,t) + PDME_2(g,t), \end{aligned} \tag{43a}$$

$$where \;\; ARRE_2(g,t) = NDP(g_{MI}, g_{PR0}, t) - NDP(g_{MI0}, g_{PR0}, t), \tag{43b}$$

$$PDME_2(g,t) = E_\chi\left[\sum_{t' \le t} \left\{\widehat{D}^\chi(t', \phi_{t'}, g_{MI0}, g_{PR0}) - \widehat{D}^\chi(t', \phi_{t'}, g_{MI}, g_{PR0})\right\}\right] \tag{43c}$$

Finally, since both cases could be chosen arbitrarily, the decomposed effects are identified by the means of the two cases as follows:

$$DRRE(g,t) = \frac{1}{2}\{DRRE_1(g,t) + DRRE_2(g,t)\} \tag{44a}$$

$$CPEE(g,t) = \frac{1}{2}\{CPEE_1(g,t) + CPEE_2(g,t)\} \tag{44b}$$

$$ARRE(g,t) = \frac{1}{2}\{ARRE_1(g,t) + ARRE_2(g,t)\} \tag{44c}$$

$$PDME(g,t) = \frac{1}{2}\{PDME_1(g,t) + PDME_2(g,t)\} \tag{44d}$$

4.16. Calibration, data needs, and computation strategy

The presented DYNAMMICs model framework is a macroeconomic model representing an economy. It delivers insights into the growth path and its components of the economy over time using a dynamic framework with stochastic components and empirical calibration.[12] To do so its inputs are adapted to observed numbers from statistical assessments. Specifically, the model needs to be calibrated using biophysical and macroeconomic statistics. The biophysical assessment statistics are needed to calibrate the damage rate as well as the effectiveness of DRR stock in the model. These contribute to the setup of various aspects of the model such as the hazard part (section 4.3). Examples for the data needed for calibration in this respect are probabilities for floods and hurricane damage rates. In addition, the model calibration takes as inputs macroeconomic statistics such as Input-Output tables to adapt the production functions (e.g. equations 6a and 6b in section 4.6) to reflect empirical observations. Examples include demand, consumption, investment, and export in the sectors included in the model economy. Further sources are needed to evaluate various elasticity parameters. The calibrated model then quantifies and allows for decomposition of DRR growth effects in the given economy and with respect to the initial empirical observations. In practice when applying the model there is a vast number of parameters requiring calibration. For any new application, a detailed comparison of data needs and availability needs to be compiled to determine which parameters can be calibrated using observed data. In some cases where data might be unavailable or of low quality the corresponding parameter values might be set by conducting a sensitivity analysis.

To cope with the “Curse of dimensionality”, this study applies a computational strategy limiting a class of the optimization. Although the optimal decision $d^*(s)$ is ideally made under the state vector s, in the computing implementation each optimal decision currently depends on a part of elements of the vector s as well as the baseline level of each decision. For example the model defines that the level of investment in production capital is determined by several components such as i) the scale of budget for all kinds of investment that reflect GDP, external assets, insurance claims, etc., ii) the baseline investment rate, and iii) the rate increment due to hurricane. Those components are selected so that such decision rules are in line with past investigation and observations. The solution algorithm is then applied to search for optimal levels for the components, thereby reducing computational load compared to fully dynamic and stochastic optimization problems.

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[12] The dynamic stochastic macroeconomic model DYNAMMICs is based on considerations of the Real Business Cycle (RBC) modelling approach. For an introduction into the setup, a discussion of the underlying assumptions and the calibration and data needs of these types of models please refer to: Kydland and Prescott (1982), Long and Plosser (1983), Aiyagari, Lawrence and Eichenbaum (1992), Stadler (1994) and Stockman (1988)

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