Economic modeling of climate change impacts and adaptation: a review of global Integrated Assessment Models

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1. Introduction

- Generally, IAM can be defined as "**approaches that integrate knowledge from two or more domains into a single framework**" (Nordhaus, 2013).
- A full assessment cycle of climate change may involve **human economic activities, biogeochemical cycle of carbon and earth's climate system.** However, IAMs usually only contain part of them according to the modeling purpose.
- Three type of IAMs
  - **Objective optimization**
  - **Recursive equilibrium**
  - **Scenario based evaluation**
- A variety of IAMs contribute to the **decision-making about climate change mitigation and adaptation** under various regional and economic contexts.

Previous review

- **Empirical evidence** (Fussel, 2010; Fisher-Vanden et al., 2012; Wing and Fisher-Vanden, 2013);
- **Technological change** (Stanton et al., 2009; Wing and Fisher-Vanden, 2013);
- **Decision-making under uncertainty** (Stanton et al., 2009; Fisher-Vanden et al., 2012; Giupponi et al., 2013; Wing and Fisher-Vanden, 2013);
- **Decision-making involving stakeholders** (Schwanitz, 2013; Giupponi et al., 2013);
- **Interrelation between natural and socio-economic** (Giupponi et al., 2013);
- **Present actions and future responses** (Stanton et al., 2009; Fisher-Vanden et al., 2012; Giupponi et al., 2013);
- **Discount rate** (Stanton et al., 2009; Nordhaus, 2013; Giupponi et al., 2013);
- **Efficiency and equity** (Stanton et al., 2009; Fussel, 2010)
- **Sectoral, spatial or temporal details** (Giupponi et al., 2013; Wing and Fisher-Vanden, 2013);
- **Climate sensitivity and irreversible catastrophe** (Stern, 2007; Stanton et al., 2009; Nordhaus, 2013).

Research motivation and objective

- Previous review
  - only represent the general development directions of IAMs, **lacking of necessary details.**
  - seldom survey the **technological aspects.**
- This review
  - examines the practical IAM **modeling methodologies**, especially for the economic descriptions in IAMs, to distinguish which modeling technique can be used in what kind of IAM, or under some certain circumstances.
  - summarizes the available modeling methodologies for adaptation, to aim at seeking an effective approach for involving two kinds of adaptation, i.e., **proactive adaption and reactive adaptation**.

2. Review of Integrated Assessment Models

- Criteria for the available IAMs in this review
  - **global**;
  - consider **adaptation**, explicitly or implicitly;
  - is **in active development** currently or has **significant influence** on recent IAMs .
- **19 IAMs** are collected from existing literature.
- In view of the important position of **objective optimization models** in IAMs and the ability to capture intertemporal feedbacks, this analysis focuses on the objective optimization models.

Global Integrated Assessment Models (IAMs) with climate change adaptation

Model	Type	Production function	Impacts	Adaptation	References
Objective optimization					
Ada-BaHaMa	max.(dis.uti.)	ext. C-D	h.s.	proa.	*Bahn et al. (2012)*
AD-DICE (1999, 2007)	max.(dis.uti.)	CRS C-D	aggr. quad.	reac.	*de Bruin et al. (2009a,b); de Bruin and Dellink (2011)*
AD-FAIR	min.(cost)	none	aggr. quad.	reac.	*Hof et al. (2009, 2010)*
AD-RICE (1999)	max.(dis.uti.)	CRS C-D	aggr. quad.	reac.	*de Bruin et al. (2009a)*
AD-WITCH	max.(dis.uti.)	nested CES	aggr. quad.	proa. & reac.	*Bosello et al. (2009, 2010, 2013)*
AIM/Impact[Policy]	max.(dis.uti.)	nested CES	sect.	water, flood, LU	*Kainuma et al. (2003)*
DICE (1992-1994, 1999, 2008, 2013)	max.(dis.uti.)	CRS C-D	aggr. quad.	imp.	*Nordhaus (1992); Nordhaus and Boyer (2000); William D.*
MERGE (2, 3, 5.1)	max.(negi.dis.uti.)	nested CES	h.s.	imp.	*Nordhaus (2008); Nordhaus and Sztorc (2013)*
RICE (1999, 2001, 2010)	max.(dis.uti.)	CRS C-D	aggr. quad.	imp.	*Manne et al. (1995); Manne and Richels (1999, 2005)*
WITCH	max.(dis.uti.)	nested CES	aggr. quad.	imp.	*Nordhaus and Boyer (1998, 2000); William D. Nordhaus*
Recursive equilibrium					
ENVISAGE	CGE	CES	lin., quad.	n.a.	*van der Mensbrugghe (2010)*
EPPA	CGE	nested CES	sect.	market-based	*Paltsev et al. (2005); Reilly et al. (2012)*
GCAM 3.0	PE	Leontief	sect.	agri.	*Wise et al. (2009); Calvin et al. (2012)*
GLOBIOM	PE	Leontief	sect.	agri. mana.	*Havl´ık et al. (2011)*
ICES	CGE	C-D	sect.	market-driven	*Eboli et al. (2010); Bosello et al. (2012)*
Scenario based evaluation					
DIVA (3.2.0, 3.4.0)	database	none	sea-level rise	scen.	*Hinkel et al. (2011, 2012); Arnell et al. (2013)*
FUND (3.3, 3.5, 3.6, 3.7)	scen. based	none	aggr. sect.	agri. & coast	*Anthoff et al. (2009); Tol (2009a); Anthoff and Tol (2013a,b)*
IMAGE 2.4	scen. based	none	sect.	LU	*Bouwman et al. (2006); van Vuuren et al. (2011)*
PAGE (2002, 2009)	scen. based	none	sea level, econ., non-econ.	scen.	*Hope (2006, 2009, 2011)*

Mitigation and adaptation for addressing climate change

Options	Mitigation	Adaptation
How to do?	• **reducing** GHG emissions • **exploiting** carbon sinks	• **adjustment** in natural or human systems • **benefit** from opportunities associated with climate change
What to do?	• improving energy efficiency • substituting with low-carbon/carbon free energy • CCS	• coastal protection/dykes • early warning systems • changing crop types/irrigation • improving medical care to avoid tropical diseases • space heating and cooling • migration
Where to do?	local/regional level	local/regional level
When it works?	**long-term**	• proactive measures: **medium- to long-term** • reactive measures: **immediately**
Effects	**reduce emission level**	**reduce the impacts** of climate change
Scopes	**global scale** benefits	**regional or local** impacts
Advantages	**permanently** eliminate/reduce the long-term risk and hazards of climate change	• has **short run effects** and easier to be promoted by local governments • selective to take advantage of positive impacts and reduce negative ones
Disadvantages	• "**freeriding problem**" among countries or regions • require concerted and simultaneous actions to foreclose leakage	• may **encourage unsustainable** emission • optimal levels of adaptation cannot be achieved due to climate change uncertainty • benefits are difficult to quantify • usually require increased energy use

3. Economic integration of factor inputs

- One of the considerable questions is how to integrate different **factor inputs** in IAMs, especially for the objective optimization models.
- The long-term assessment oriented objective optimization model usually integrate different factor inputs by a **production function** according the objective of the model.
- **Capital stock and labor** are two primary factors used in most of the objective optimization models, which reflect the economic development levels and population trends, respectively, and they also provide a **direct route** to involve a specific scenario with prescribed economic and population development projection.
- Aggregation of energy is **a skillful work** due to its significant position.

Production function in objective optimization models

- DICE/AD-DICE

$$Y = A \cdot K^{\alpha} \cdot L^{1-\alpha}$$

- RICE/AD-RICE

$$Y = A \cdot K^{\alpha} \cdot L^{\beta} \cdot ES^{1-\alpha-\beta}$$

- MERGE, AIM/Impact[Policy]

$$Y = A \cdot [a \cdot (K^{\alpha} \cdot L^{1-\alpha})^{\rho} + b \cdot (EE^{\gamma} \cdot NE^{1-\gamma})^{\rho}]^{1/\rho}$$

- WITCH/AD-WITCH

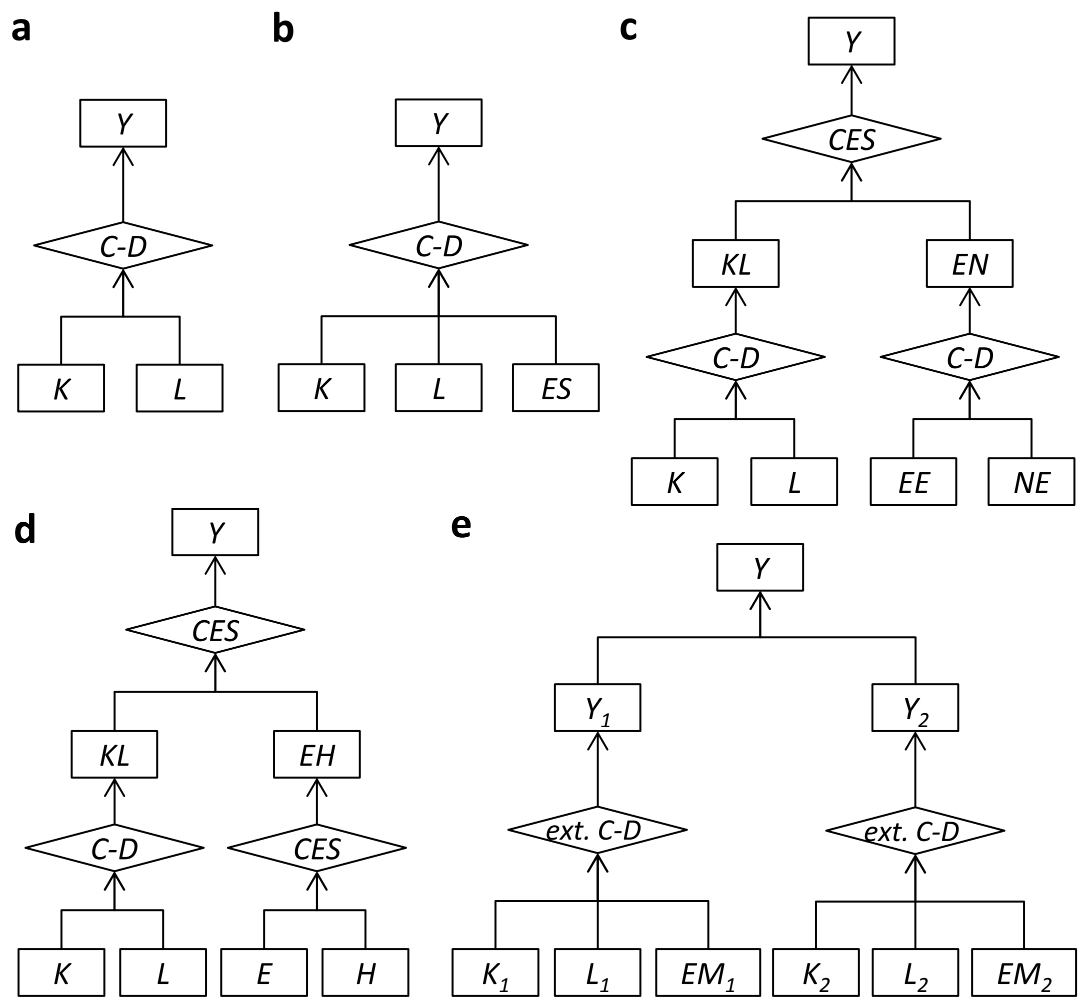
$$Y = A \cdot [a \cdot (K^{\alpha} \cdot L^{1-\alpha})^{\rho} + (1-a) \cdot EH^{\rho}]^{1/\rho}$$

$$EH = (a_E \cdot E^{\rho_{EH}} + a_H \cdot H^{\rho_{EH}})^{1/\rho_{EH}}$$

- Ada-BaHaMa

$$Y = A_1 \cdot K_1^{\alpha_1} \cdot L_1^{\beta_1} \cdot (\phi_1 \cdot EM_1)^{1-\alpha_1-\beta_1} + A_2 \cdot K_2^{\alpha_2} \cdot L_2^{\beta_2} \cdot (\phi_2 \cdot EM_2)^{1-\alpha_2-\beta_2}$$

Production nests in IAMs (1)



Production nest in objective optimization IAMs

Notes: a. DICE/AD-DICE; b. RICE/AD-RICE; c. MERGE, AIM/Impact[Policy]; d. WITCH/AD-WITCH; e. Ada-BaHaMa

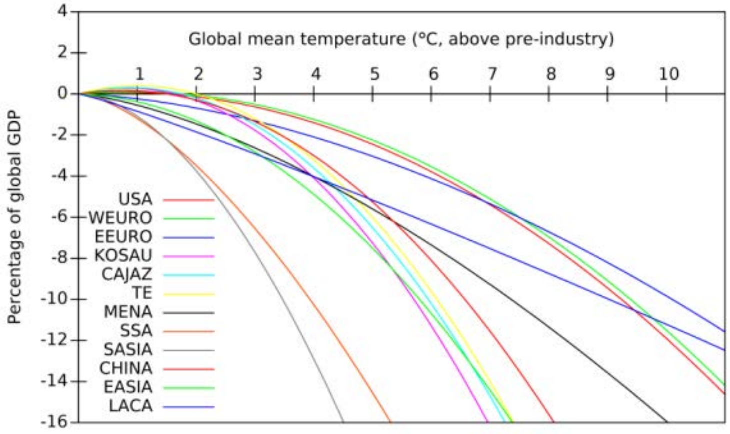
Production nests in objective optimization IAMs (2)

- The most used production functions: **C-D and CES**
- **Constant returns to scale** is assumed in both the C-D production functions, e.g., DICE/AD-DICE, RICE/AD-RICE and Ada-BaHaMa, and CES production functions, e.g., MERGE , AIM/Impact[Policy] and WITCH/AD-WITCH models. These assumptions may reduce the complexity of the optimization process, despite it is usually not the case in real economy.
- **Up to two levels of nested production function** are mostly used, such as MERGE, AIM/Impact[Policy] and Ada-BaHaMa.
- The **two-level CES nested structure**, which combine capital-labor value added in the first level, and then aggregate energy in the second level with both CES production functions, may fit the historical economic data well. It also provides an implication to adopt this kind of nested structure in IAMs.

4. Climate change impacts

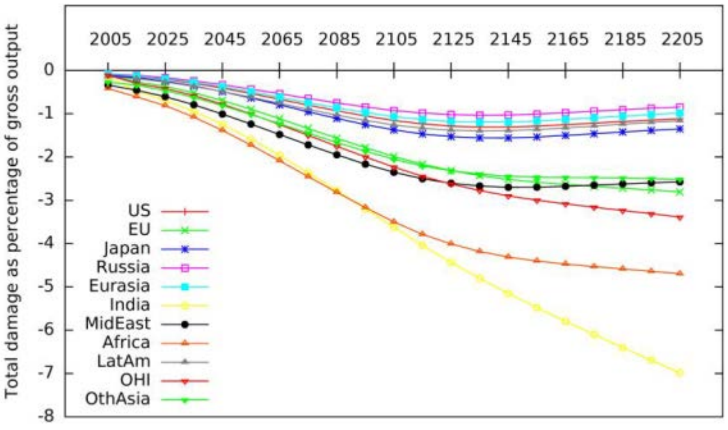
- Assessment of climate change impacts is indispensable for the IAMs and it measures how much does the climate change affect **human development and economic activities**.
- Without the introduction of climate change impacts, IAMs will lack the feedback which influences current decision making of climate change policy.
- Two types of impacts are introduced in most IAMs: **biophysical impact and monetary aggregated impact**, globally or regionally.
- The monetary aggregated impact is usually estimated from biophysical impact.

Regional aggregated impacts



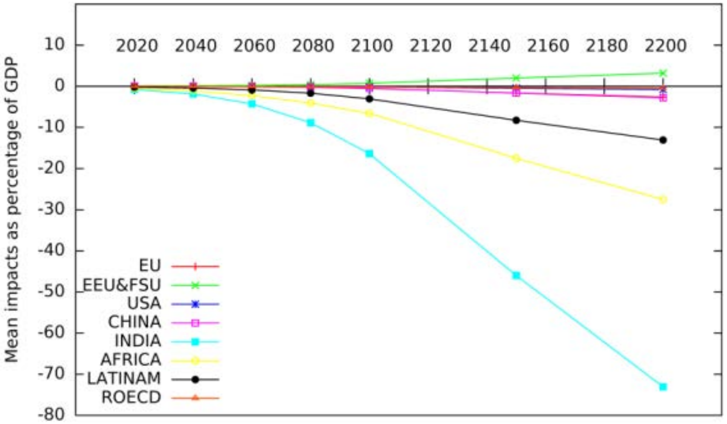
Gross damages in AD-WITCH model

Sources: Cian and Ferranna (2012)



Total damages in the optimal scenario of RICE 2010 model

Sources: Total damages of RICE model are calculated from RICE 2010 source codes.



Total mean impacts in FUND model

Sources: Warren et al. (2006)

For regional damages in RICE, WITCH/AD-WITCH

- The regional impacts are usually estimated according to the **aggregation impacts** from different sectors or endpoints.
- Nordhaus and Boyer (2000) represent an ideal for how to integrate the climate change damages in the IAMs.
- For both estimations from RICE (2010) and AD-WITCH model, **India or South Asia** suffers the largest climate change damages because of the impacts on **agriculture** and the severe damages from **catastrophic climate phenomenon.**
- However, for **Africa**, the climate change has threatening impacts on **human health** considering current poor health care conditions.
- An approximate estimation of 2 °C increase will have positive impacts for USA, WEURO, KOSAU, CAJAZ, TE and CHINA in AD-WITCH, due to the beneficial effects on **agriculture or non-market time use.**

For regional damages in FUND

- Unlike the RICE/AD-RICE type assessment of climate change impacts as direct damages on economy, the FUND model attempts to consider the **non-benchmark climate change and socio-economic vulnerability**.
- Still, the FUND model distinguishes climate change damages between market and non-market, similar as MERGE model, but more **detail effects** are differentiated concerning different aspects of the economy, for example, market damages affect investment and consumption while non-market damages only affect welfare.
- As to the human health, the FUND model uses **both biophysical and monetary metrics** to measure the impacts from heat/cold related stress and vector-borne diseases.
- In addition, the climate change impacts are determined not only by **GMT change**, but also by other factors, i.e., **sea-level rise, wind storms, river floods and CO_2 concentrations**.

Global aggregated impacts

- The quadratic damage function

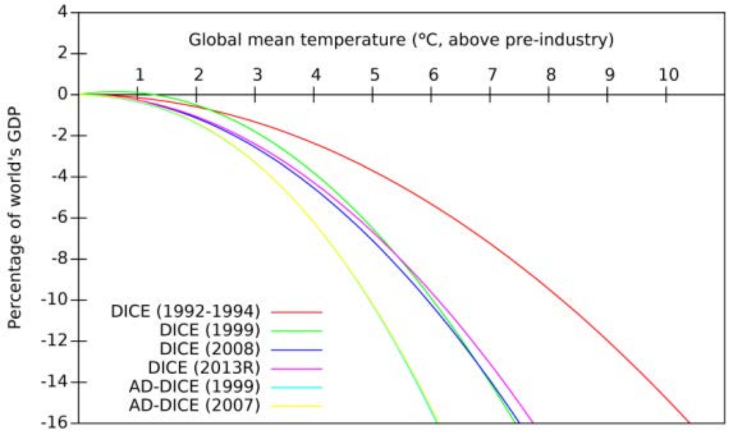
$$d(t) = \delta_1 \cdot T(t) + \delta_2 \cdot T(t)^{\delta_3}$$

- Damages estimation in MERGE model

$$dm(n,t) = d_{1,n} \cdot T(t)^{d_{2,n}}$$

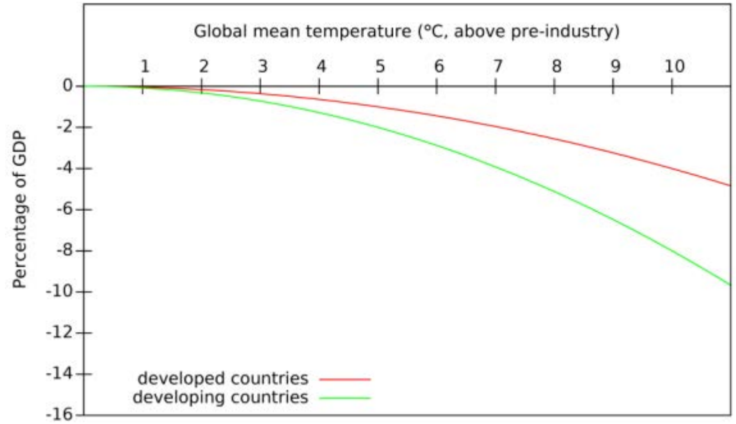
$$WTP(n,t) = \frac{d_{3,n} \cdot T(t)^{d_{4,n}}}{1 + 100 \cdot exp\left(-0.23 \cdot \frac{GDP(n,t)}{Pop(n,t)}\right)}$$

Damages estimation in DICE/AD-DICE, MERGE



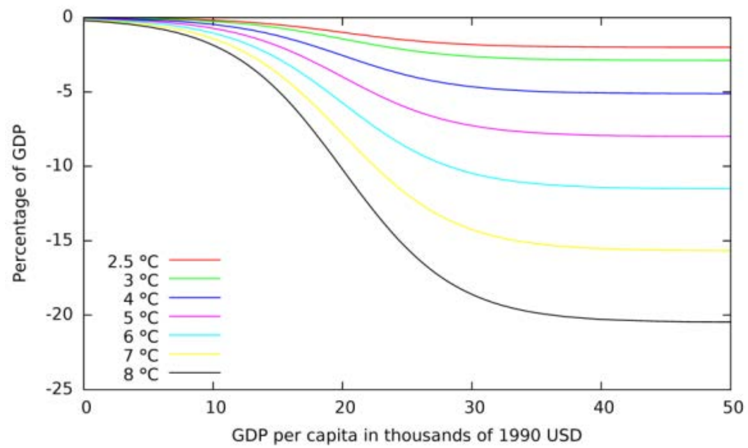
Climate change damages as a percentage of world's GDP from DICE/AD-DICE model

Sources: Damages of DICE model (1992-1994, 1999, 2008, 2013) are calculated from the specific version of source codes; AD-DICE (1999): de Bruin et al. (2009b), AD-DICE (2007): de Bruin et al. (2009a).



Market damage in MERGE model

Sources: Manne et al. (1995)



Non-market damage in MERGE model

Sources: Manne et al. (1995)

For damages estimation in DICE/AD-DICE

- The quadratic equation is capable of reflecting an increasing GDP loss trend in future due to the climate change. However, the economy may gain a slight **benefit** in the lower temperature change, because of the **positive impacts from agriculture, other vulnerable market and non-market time use**.
- The positive impacts are achieved by **a negative intercept parameter** in the quadratic function, and recent evidence has also confirmed the short-term profit of climate change in some sectors, especially for **agriculture**, that the regions of the mean temperature lower than the inherent optimal temperature for crops growth will benefit from temperature increase in certain degree.
- The total damages of AD-DICE (1999, 2007) are **gross damages**, covering the damages avoided through adaptation and it evidently leads to higher GDP losses than those in DICE serial models.

For damages estimation in MERGE

- MERGE model deals with the climate change impacts with **market and non-market** separately, differentiating the intangible damages caused by non-market behavior from general market impacts.
- The market damages for developing countries are **lager** than those of developed countries because of weaker ability to withstand climate change.
- The non-market damages follows a WTP approach which defines the maximum amount a person being willing to pay depends on the **per-capita income** and the curve shows **an inversed “S” shape.**
- There is a GDP per capita income interval within which the WTP increases rapidly. It indicates that low-income countries are willing to set aside **limited** budget for solving the problem of climate change; as income increases, the willingness to pay for climate change **increases promptly** until a certain level that the investment or expenditure is no longer efficiency for dealing with climate change.
- Also, the higher temperature climate change causes, more **rapid growth** are found with respect to the investment or expenditure for climate change.

5. Modeling adaptation

- Adaptation to climate change means to reduce the **exposure or vulnerability** of human society and ecosystems so as to prevent or minimize the climate change damages.
- Generally, adaptation is classified as **proactive activities**, which moderate the climate change damages by protective investment treated as long-term stock, and **reactive activities** that alleviate the impacts on sectoral productivity treated as short-term flow.
- Recent IAMs with explicit adaptation either embed one of the adaptation type or simulate both.
- Besides, current adaptation modeling usually assumes **an additional investment or expenditure** for climate change adaptation, based on existing sectoral estimation.
- The relevant results center on **the relationship between mitigation and adaptation, the efficiency to reduce climate change costs or the impacts on GHGs emission path and atmospheric carbon concentration**.

Reactive adaptation modeling in AD-DICE model

- A simplified modeling approach of reactive adaptation is to separate the **flow adaptation** expenditure from net damages, and distinguish the **adaptation benefits** from the gross damages.

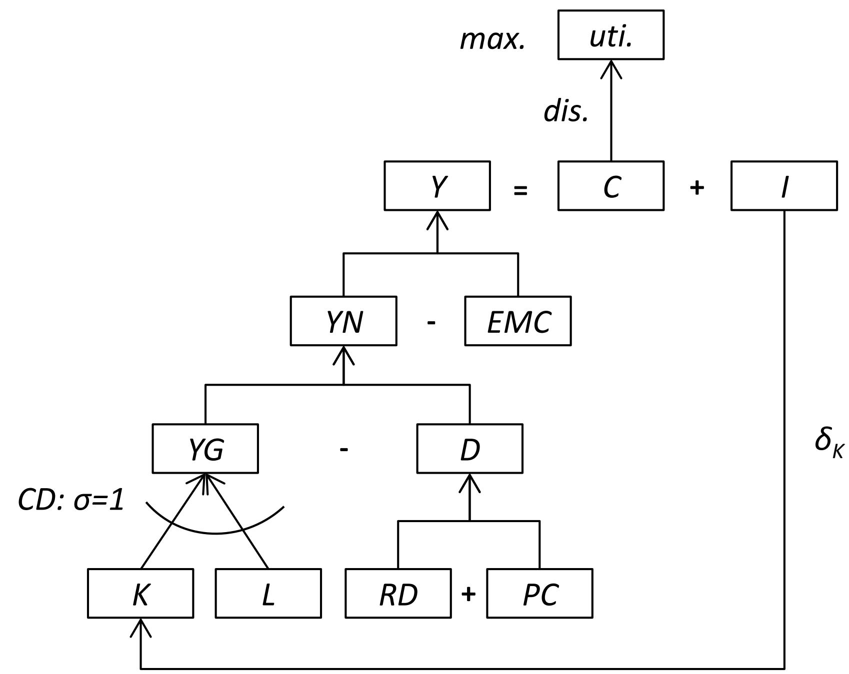
$$d(t) = \frac{D(t)}{Y(t)} = \frac{RD(GD(t), P(t))}{Y(t)} + \frac{PC(P(t))}{Y(t)}$$

$$RD(t) = GD(t) \cdot (1 - P(t))$$

$$\frac{PC(t)}{Y(t)} = \lambda_1 P(t)^{\lambda_2}$$

$$YN(t) = \frac{1}{1 + d(t)} \cdot YG(t)$$

- For modeling of reactive adaptation, this approach is rather **straightforward and concise.**
- However, more **sectoral details** are needed if one wants to clarify the cost for a certain sector and the resulting benefit.
- Meanwhile, improvement should be made to the related **empirical estimation** of costs and benefits of reactive adaptation.



Reactive adaptation modeling in AD-DICE

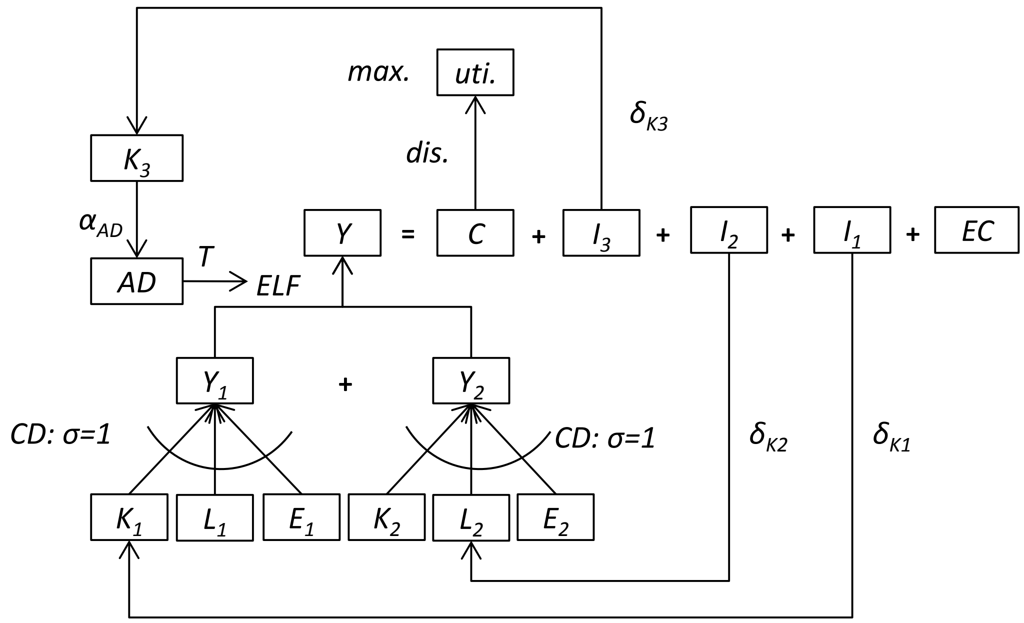
Proactive adaptation modeling

- For the production output of a certain period, **a specific budget** is allocated for dealing with long-term climatic adaptation

$$ELF(t) \cdot Y(t) = C(t) + I_1(t) + I_2(t) + I_3(t) + EC(t)$$

$$ELF(t) = 1 - AD(t) \cdot \left(\frac{T_{AT} - T_d}{cat_T - T_d}\right)^2$$

- For the **lagging return of adaptation investments**, it is not modeled appropriately that the lessen damages will take effect in the same period by the direct multiplication of *ELF*.
- The adaptation modeling in Ada-BaHaMa reflects the **aggregated investments and benefits, and sectoral details** are difficult to be integrated.
- Reliable **empirical estimation** is also absent with respect to recent impacts and adaptation research.



Adaptation modeling in Ada-BaHaMa

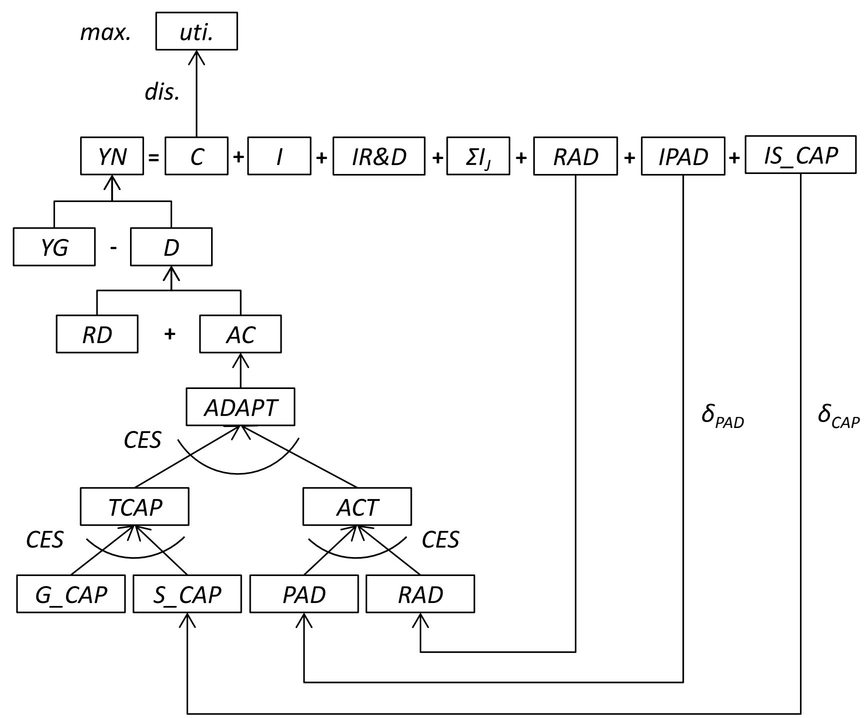
Integrate reactive and proactive adaptation in AD-WITCH

- The production output is allocated for **consumption and the investments or expenditure on innovation, energy technologies, reactive adaptation expenditure, investment for proactive adaptation and investment for specific adaptation.**

$$YN(n,t) = C(n,t) + I(n,t) + IR\&D(n,t) + \sum_{J} I_{j_{n,t}} + RAD(n,t) + IPAD(n,t) + IS\_CAP(n,t)$$

$$RD(n,t) = YN(n,t) \cdot \frac{1}{1 + ADAPT(n,t)} \cdot \left(\delta_{1,n} \cdot T(t) + \delta_{2,n} \cdot T(t)^{\delta_{3,n}}\right)$$

- There is similar problem with the **long-term return** of proactive investment as in Ada-BaHaMa.
- The separation of different adaptation measures in AD-WITCH can yet be regarded as a comprehensive IAM about adaptation, the only problem is still the lack of **empirical statistic data** for reliable simulation of the climate change costs and benefits, unlike the mitigation, which has detailed **technological and economic assessment** for different mitigation measures.



Adaptation modeling in AD-WITCH

Conclusions

1. It is practical for current objective optimization Integrated Assessment Models to consider either **sectoral details or regional details**, rather than both of them synchronously due to the computational complexity.
2. As to the proactive adaptation, the character of **time lag** should be modeled explicitly.
3. To conduct adaptation, differentiation should be made to the needs of climate change adaptation from the needs of **economic development and population growth**, as well as the **autonomous technological change** for adaptation.
4. It is important to distinguish between **sectors or endpoints** with respect to climate change impacts and this would help model developers to provide additional detailed information about climate change mitigation and adaptation.
5. The Integrated Assessment Models also need to consider the emerging **climate engineering**, including both carbon dioxide removal and solar radiation management.

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