Using Small Models for Big Issues: Exploratory System Dynamics Modelling and Analysis for Insightful Crisis Management

Erik Pruyt – E.Pruyt@tudelft.nl
Faculty of Technology, Policy and Management; Delft University of Technology
P.O. Box 5015, 2600 GA Delft, The Netherlands – E-mail: e.pruyt@tudelft.nl

11 June 2010*

Abstract

The main goal of this paper is to explain and illustrate different exploratory uses of small System Dynamics models for analysis and decision support in case of dynamically complex issues that are deeply uncertain. The applied focuss of the paper is the field of inter/national safety and security.
The need for exploratory approaches is first of all discussed. Different exploratory System Dynamics approaches are then briefly introduced. Thirdly, a typology of safety and security issues/crises –in terms of degrees of complexity, uncertainty and urgency– is proposed. Different types of inter/national safety and security issues for which exploratory analyses may be useful are listed too. And the application of these exploratory approaches is subsequently illustrated on some of these issues, more precisely on (i) an acute micro-prudential financial crisis (the concerted run on the DSB Bank), (ii) an imminent A(H1N1)v flu crisis, and (iii) plausible mineral/metal scarcity crises. The paper ends with conclusions, lessons learned, and a discussion of future work.

Keywords: Exploratory System Dynamics, Exploratory Modelling and Analysis, Crisis Management, Safety and Security, ESDMA

1 Introduction

1.1 The Need for Improving Exploratory & Analytical Capabilities

Governments and agencies are, on the one hand, supposed to be able to cope with serious safety and security threats/crises of ever different kinds (acute and smoldering, short term and long term, global and local), and ever higher degrees of complexity, uncertainty, and interconnectedness. Governments and agencies realise, on the other hand, that they cannot possibly build specific capabilities and capacities for dealing with each and every imaginable risk or crisis.

Full-hazard risk analyses like the Dutch National Risk Assessment (Bergmans, van der Horst, Janssen, Pruyt, et al. 2009) (Pruyt and Wijnmalen 2010) (Rademaker 2008) therefore often direct towards building generic capabilities –capabilities that can be used for different sorts of risks or crisis situations. A generic capability that often needs to be improved –especially for dealing with complex and uncertain crises– is the analytical capability to develop useful insights and support policymaking. The more complex and uncertain safety and security issues become, the more important this capability becomes. It may be crucial –especially in inter/national safety and security

*Published as: Pruyt, E. 2010. Using Small Models for Big Issues: Exploratory System Dynamics Modelling and Analysis for Insightful Crisis Management. *Proceedings of the 18th International Conference of the System Dynamics Society*, 25-29 July 2010, Seoul, Korea. (Available online at `http://www.systemdynamics.org`.)

issues– to consider *dynamic complexity* and *deep uncertainty*, without trying to pursue overly detailed analyses and falling into the prediction fallacy.

Dynamic complexity is found in 'situations where cause and effect are subtle, and where the effects over time of interventions are not obvious' (Senge 1990). It arises, among else, from the complex interactions of systems, markets, institutions, products, regulators, (groups of) actors, and policies/regulations.

Lempert, Popper, and Bankes (2003) define **deep uncertainty** as situations 'where analysts do not know, or the parties to a decision cannot agree on: *(i)* the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future [e.g. different drivers and underlying structures than today], *(ii)* the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or *(iii)* how to value the desirability of alternative outcomes'.

Conventional forecasting, planning, and analysis methods are not equipped to deal with dynamic complexity (Senge 1990) and even less so to deal with deep uncertainty: prediction of dynamic behaviours and certainty about probabilities, validity, and optimality cannot be obtained for (future) multi-dimensional systems characterised by high degrees of dynamic complexity and deep uncertainty. Moreover, improving models by increasing the level of detail or their size does mostly not help much: after all, 'all models are wrong [but] some are just more useful' (Sterman 2002a). Improving models by increasing the level of detail or their size may even be harmful if there is little time to act, since increasing the level of detail or the size of models is very time-consuming.

Instead of focussing on predictability, optimality, and attempting to develop ever more detailed models validated upon past conditions, it may be more useful to develop small fast-to-build models, *explore* different model formulations and a plethora of uncertainties, and test effectiveness and robustness of policies in the face of these parametric and structural uncertainties. Hence, there is a real need for innovative and useful methods to explore the influence of extreme conditions and uncertainties on the dynamic complexity of such systems.

Traditionally, System Dynamics (SD) is used for modelling and simulating dynamically complex issues and analysing their resulting non-linear behaviours over time in order to develop and test the effectiveness (and robustness) of structural policies (see subsection 2.1 on page 3 for a brief explanation of traditional SD and typical SD diagrammatic conventions). Mainstream System Dynamicists have assumed for decades that uncertainties are omnipresent, and hence, that trajectories generated with SD simulation models should not be interpreted quantitatively as point or trajectory predictions, but that they should be interpreted qualitatively as general 'modes of behaviour'. And although univariate and multivariate sensitivity analyses are mostly performed, they are mainly aimed at validation – not exploration. It seems therefore that in traditional SD uncertainties are accepted but are not really explored or explicitly taken into account.

However, SD models may also be built specifically for the purpose of exploring the potential influence of uncertainties on dynamically complex issues. Such Exploratory System Dynamics (ESD) models are preferably fast-to-build and easily-manageable models, and consequently, rather simple and highly aggregated. In this paper, it will be argued and shown that ESD is an interesting approach for exploring different model formulations and a plethora of uncertainties, and testing the effectiveness of policies in the face of these parametric and structural uncertainties. However, ESD in isolation may –as argued below– be insufficiently broad and systematic to firmly base policymaking under deep uncertainty on.

But the combination of ESD with Exploratory Modelling and Analysis (EMA – see subsection 2.3) may be useful and sufficient for broadly and systematically exploring and analysing plausible developments of crises and their impacts, and for testing the effectiveness and robustness of preventive and curative policies without neglecting deep uncertainty and dynamic complexity.

EMA consists of using exploratory models (not necessarily SD models) for generating tens of thousands to millions of scenarios (called an ensemble of future worlds) in order to analyse and test the robustness of policy options across this ensemble of future worlds – in other words whether the outcomes are acceptable over the entire scenario space. As such, it can be used to generate insights and understanding about the functioning of systems and the robustness of policies, by taking deep uncertainty seriously into account (Lempert, Popper, and Bankes 2003) (Agusdinata 2008). In EMA, the question is not 'when to measure more' nor 'when to model better', but 'how to explore and analyse dynamically complex systems under deep uncertainty', and 'which policies do effectively and robustly improve system behaviour under deep uncertainty'.

Since EMA requires handy models for generating (thousands of) plausible scenarios, and ESD requires methods for exploring deep uncertainty, they are actually natural complementary allies (Pruyt 2007), and can be combined as Exploratory System Dynamics Modelling and Analysis (ESDMA).

1.2 Organisation

The main goals of this paper are therefore to introduce ESD, EMA, and ESDMA, and illustrate them by providing examples of different applications in the field of inter/national safety and security that may require such approaches.

The constitutive elements of ESDMA are introduced in more detail in section 2: traditional SD is briefly introduced in subsection 2.1, the difference with ESD is briefly discussed in subsection 2.2, and the core ideas of EMA are briefly outlined in subsection 2.3. Both constitutive elements are brought together in subsection 2.4.

Recognizing that the type of methodological support required depends on the type of crisis, a typology of inter/national safety and security issues/crises is proposed in section 3. Examples of different types of inter/national safety and security crises –for which ESD and/or ESDMA may be useful– are provided there as well. Some of these examples are elaborated in subsections 4.1 to 4.3. An example of an acute bank crisis is elaborated in subsection 4.1. The example of a possibly catastrophic flu pandemic is elaborated in subsection 4.2. And the smouldering issue of plausible mineral/metal scarcity is elaborated in subsection 4.3. Concluding remarks and venues for future work are presented in section 5.

2 From SD to ESD, and from ESD + EMA to ESDMA

It may be useful for readers without System Dynamics foreknowledge to get acquainted to SD and its diagrammatic conventions before reading the remainder of this paper. Readers familiar with the System Dynamics approach are advised to skip subsection 2.1 and start with subsection 2.2.

2.1 Traditional SD and SD Diagramming Conventions

System Dynamics (SD) simulation models consist of stock-flow structures linked by positive or negative causal links into positive and negative feedback loops. The Stock-Flow Diagram (SFD) in Figure 1, which graphically represents an (exploratory) SD simulation model –related to a share-price signalled bank crisis like the Fortis Bank crisis (Pruyt 2009b)– maps stock variables (□), flow variables (⧖), auxiliary variables and constants (no symbols) and other direct causal influences between variables (the blue arrows). Auxiliary variables often contain *time delays* (indicated by slashed arrows) and *nonlinear functions* (for which easy-to-draw lookup or graph functions are often used).

Stock variables are the state variables of the system. They can only be changed by flow variables. Positive inflows (outflows) increase (decrease) the contents of stock variables. A stock variable is the accumulation or integral of the difference between the incoming flows and the outgoing flows over the time interval considered, plus the amount in the stock at the beginning of the period. Mathematically speaking, these models are therefore systems of integral equations

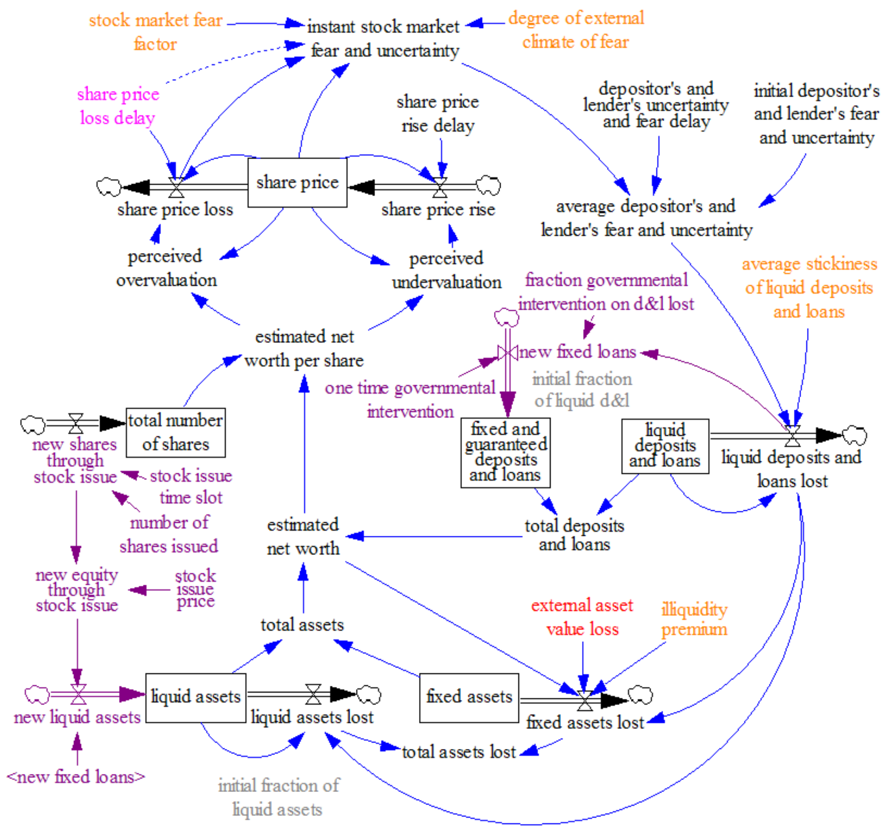


Figure 1: Stock/Flow Diagram of the Fortis Bank model with some policies in purple

(or systems of differential equations). Every feedback loop contains at least one stock variable or memory, hence, avoiding simulation problems caused by simultaneous equations.

The simulation over time of simulation models consisting of these structural elements generates the model behaviour (see Figure 2 for different modes of behaviour generated with the Fortis Bank SD model displayed in Figure 1). One of the basic assumptions of SD is that the structure of a system (and model) drives its behaviour, and hence, that structural policies are required to effectively and robustly change (or prevent) undesirable behaviours.

System Dynamicists do not use SD for exact point or path prediction because they are aware of the fact that –with traditional SD– too many uncertainties remain unexplored (Meadows and Robinson 1985). Hence, they interpret quantitative trajectories as qualitative modes of behaviour.

Feedback loops consist of two or more causal influences between elements that are connected in such a way that if one follows the causality starting at any element in the loop, one eventually returns to the first element. A feedback loop is called positive or reinforcing (⊕ or ⊕) if an initial increase (decrease) in a variable A leads after some time to an additional increase (decrease) –above (below) what would have been the case otherwise– in A. In isolation, they generate exponential growth or decay. A feedback loop is called negative or balancing (⊖ or ⊖) if an initial increase (decrease) in variable A leads after some time to an additional decrease (increase) –or a smaller increase (decrease) than would have been the case otherwise– in A. In isolation, they generate balancing or goal-seeking behaviour and can be used for automatic control/balancing. Hence, they generate nonlinear behaviour, even if all constitutive causal relationships are linear. Feedback loops almost never exist in isolation: they are often strongly coupled, and their respective strengths change over time.

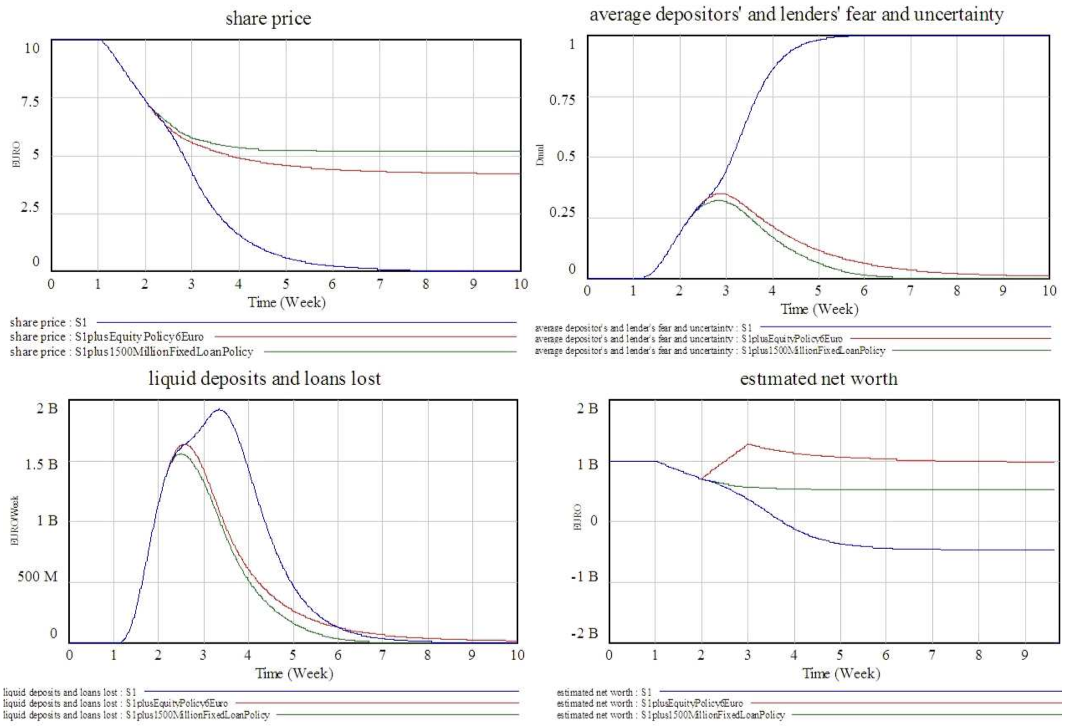


Figure 2: Behaviour of the 'share-price signalled bank crisis' model and behaviours of two strategies to save the (Fortis) bank from collapsing – see (Pruyt 2009b)

Mainstream SD[1] is all about making and using models in order to get a better understanding of the link between modelled system structure and modelled system behaviour in order to be able to improve the behaviour of the real system by changing the real system structure. Mainstream SD is therefore useful for improving the general understanding, and for high-level policy analysis, but not for detailed operational analysis nor for trajectory forecasting/prediction. Traditional SD is, in this sense, already rather exploratory.

After this unitary perspective on the SD field, it should be noted that there are –apart from mainstream SD– different SD practices in use, from purely qualitative over mixed quantitative-qualitative to purely quantitative, from very small models to huge models, and from postpositivist over pragmatist, critical-pluralist and transformative-emancipatory-critical to constructivist (Pruyt 2006)(Lane 2001a)(Lane 2001b). Given the existence of these fundamentally different SD approaches, there is also room for fundamentally different ESDMA approaches.

2.2 Exploratory System Dynamics (ESD)

Exploratory System Dynamics (ESD) refers to the use of fast-to-build, relatively-small, highly-simplified, data-poor, easy-to-use SD models for quick/easy exploration of (a plethora of) possible behaviours and plausible scenarios, and for developing a rough idea about the effectiveness –and to a lesser extent the robustness– of potential policies.

As such, it may be used to quickly explore plausible behaviours with a relatively simple model –or relatively simple models– without explicitly aiming to uncover *the* structures underlying the real issue and forecasting *the* behaviour or *the* probabilities of the behaviours.

[1] See (Forrester 1968) (Meadows and Robinson 1985) (Ford 1999) (Sterman 2000), etc.

The focus of ESD lies then on testing whether behaviours of interest (e.g. plausible trajectories that require attention) can be generated (at all), on exploring plausible types of behaviours, and on identifying policies that may be effective. Traditional tools such as scenario analysis, risk analysis and what-if analysis can be used in ESD too, but in view of a different goal than in traditional SD (exploration instead of model validation).

the issues for which ESD is useful are just too uncertain and complex, and that the ESD models developed are just too wrong[2] for any form of prediction (but also more useful for the purpose of exploration).

ESD could be used for generating interesting behaviours, plausible trajectories that require attention, test whether specific behaviours can be generated at all, etc. It cannot be used to make predictions or derive firm conclusions about specific values or sets of conditions that may lead to this or that behaviour, or to interpret outcomes in a probabilistic sense. Hence, ESD may be good as an introduction to dealing with complex and uncertain issues, especially for imagining plausible modes of behaviour; it is not useful for detailed analysis in view of detailed implementation or to (totally) reduce uncertainties. ESD modelling is thus most appropriate for quick and dirty modelling if time is at a premium and for assumption based modelling if uncertainties are too deep for traditional approaches.

Although ESD in isolation may be appropriate for some issues and purposes, it may also be insufficiently systematic for well-founded decision support for issues characterised by deep uncertainty. ESD may still be useful for that purpose, but then as a scenario generator for EMA (see section 2.4).

2.3 Exploratory Modelling and Analysis (EMA)

Exploratory Modelling and Analysis (EMA) can be used (i) to explore the influence of uncertainties[3], and (ii) to test the effectiveness and robustness of policies given all these uncertainties.

EMA consists more precisely of (i) developing 'exploratory' –fast and relatively simple– models of the issue of interest, (ii) generating an ensemble of future worlds (thousands to millions of scenarios) by sweeping uncertainty ranges and varying uncertain structures and boundaries, (iii) simulating and analysing the dynamic behaviours, bifurcations, et cetera, (iii) and/or specifying a variety of policy options (preferably adaptive ones), and simulating, calculating, and comparing the performance of the various options across the ensemble of future worlds.

Although data analysis techniques (step (iii)) could be used to investigate the effect of underlying mechanisms/(inter)actions/conditions, to separate different modes of behaviour, to determine the conditions that lead to these different modes of behaviours, to find bifurcation points and critical variables, it may be even more interesting to define different (adaptive) policies/strategies and immediately test their (relative and absolute) effectiveness/robustness given all these uncertainties (step (iv)). The effectiveness/robustness of policies can then be evaluated over the entire multidimensional uncertainty space without needing to analyse/understand millions of outcomes. In other words, the effectiveness/robustness of policies/strategies could be evaluated and compared without reducing uncertainties related to the system of interest and without getting overwhelmed by combinatorial complexity.

EMA is still under development, among other places at RAND and Delft University of Technology. At Delft University of Technology, several researchers are currently improving, extending and contributing to EMA theory, EMA methodology, and EMA tools, and are working on a plethora of EMA applications, often in combination with adaptive policymaking[4]. Currently, special at-

[2]Note that all models are wrong, but some are just more useful (Sterman 2002b).

[3]related to initial values, parameters, specific variable formulation, generative structures, model formulations, model boundaries, different models, different modelling methods and paradigms, and different preferences and perspectives related to different world-views, and policies

[4]For RAND related EMA work see (Bankes 1993), (Lempert and Schlesinger 2000), (Lempert, Popper, and Bankes 2003), (Lempert, Groves, Popper, and Bankes 2006), (Bryant and Lempert 2009), et cetera, and for Delft University of Technology related EMA work see (Walker and Marchau 2003), (Van der Pas, Agusdinata, Walker, and Marchau 2007), (Agusdinata 2008), (Van der Pas, Agusdinata, Walker, and Marchau 2008) (Agusdinata, Van der Pas, Walker, and Marchau 2009) (Pruyt and Hamarat 2010a) (Pruyt and Hamarat 2010b) (Pruyt 2010) (Kwakkel,

tention is paid to the combination of ESD and EMA in order to ease their combined application to deeply uncertain dynamically complex issues.

2.4 Exploratory System Dynamics Modelling and Analysis (ESDMA)

In 'Exploratory System Dynamics Modelling and Analysis' (ESDMA), the fast and relatively simple models used to generate ensembles of future worlds are more specifically ESD models. Since EMA is appropriate for systematically exploring deep uncertainty and testing the robustness of policies, and ESD models are particularly appropriate for generating plausible behaviours over time, it follows that ESDMA is particularly appropriate for *systematically* exploring and analysing thousands to millions of plausible dynamic behaviours over time, and for testing the robustness of policies over all these scenarios. As opposed to EMA, ESDMA therefore goes beyond the calculation of end states or static values, which is in fact a complicating factor.

Since EMA is a quantitative uncertainty analysis approach and mainstream SD modelling consists of making quantitative simulation models, it follows that ESDMA is mainly a quantitative multi-method (see examples in subsections 4.1, 4.2, and 4.3), but which leads –just like traditional SD– to qualitative interpretations, conclusions and recommendations.

In the field of inter/national safety and security, ESDMA may for example be used to generate critical information about:

- policies that are (effective and) robust in the face of deep uncertainty,
- capabilities/capacities that need to be built no matter which future actually materialises,
- scenarios that are not covered by policies, and hence, require additional attention and/or policymaking,
- tipping points/folds or critical thresholds and critical internal/external early detection indicators that are required for monitoring their possible movement towards those tipping points or critical thresholds; and
- indications about the urgency of building necessary capabilities (e.g. plausible short term crises, or long term crises for which the capability development time exceeds the time within which the crises may possibly develop).

From an applied safety and security point of view, ESD en ESDMA may be useful before, during, and after crises. Before a crisis they may be used as part of an explorative gap analysis to analyse the gap between required and existing capabilities and capacities. At the outbreak of a crisis they may be useful for exploring plausible scenarios in order to prepare (e.g. for the worst credible), and support reflection and decision-making about possible crisis management interventions. In case of acute or imminent crisis –if time lacks to do detailed research– they may be helpful for performing quick and dirty analyses and for testing the robustness of (adaptive) policies. And after crises, they may be useful for hypothesising about the underlying structure in order to understand the crisis beyond the 'event'-level and learn from it for future crises.

Relatively simple examples –in terms of methodological complexity– are used in this paper to illustrate both ESD and ESDMA. The uncertainties dealt with relate more specifically to: (i) parameter values of exogenous variables, (ii) functions and formulations, and (iii) generative structures, loops, and submodels within one and the same model. Not dealt with here are (iv) different model formulations and model boundaries, and hence, different models, (v) different world-views, and hence, different models and preference systems, and (vi) different modelling methods and paradigms.

Walker, and Marchau 2010a) (Kwakkel, Walker, and Marchau 2010b) (Bankes, Walker, and Kwakkel 2010), etc.

3 A Typology of Safety/Security Issues/Crises

The applied safety and security issues discussed in the remainder of the paper are characterised by (different degrees and types of) dynamic complexity, uncertainty, and urgency. Urgency is defined here as the time required for analysis and action compared to the time available for analysis and action. High degrees of dynamic complexity and uncertainty make ESD and/or ESDMA useful, but the urgency determines to some extent which of these types of analysis is most appropriate. ESDMA takes much more time than ESD –weeks instead of hours– and may therefore be problematic when urgency is high and crises acute. Moreover, perceived urgency may also dictate the main type of solutions/actions to be focussed on:

- crisis management –sometimes called the third line of defence– may be the only option if perceived urgency is extremely high (e.g. acute crises);
- detection of plausible/potential threats/crises and fighting them –sometimes called the first line of defence– may be the preferred mode if perceived urgency is moderately high;
- and making the system itself more robust/resilient –sometimes called the second line of defence– may be an option if there is enough time to do so and hence perceived urgency is rather low.

Hence, the following typology of uncertain, dynamically complex safety and security issues/crises in terms of urgency (extremely urgent, urgent, not so urgent, uncertain how urgent) is proposed:

Type I: Acute Crises – extremely urgent – not much time for analysis and action

Acute crises are characterised foremost by their extreme urgency: in fact it is already too late to act preventively (first and second lines of defence) at the first signs of an acute crisis. There is room for quick and dirty analysis and for crisis management (third line of defence). The occurrence of the crisis is also uncertain until it actually happens (else preventive or mitigating action could have been taken). The dynamics of the crisis and aftermath, and hence the cumulative impacts, are often also uncertain and somewhat complex.

Examples include unanticipated real or virtual terrorist attacks, unexpected outbreaks of armed conflicts like the Rwandan genocide, and acute unthought-of crises of financial institutes (e.g. Lehman Brothers or Fortis) or systems (e.g. Black Monday/Wednesday, acute currency crises, or dept crises).

ESD may be useful for such acute crises for generating insights about possible dynamics of the crisis and aftermath that may be useful for reactive crisis management (the third line of defence).

Fully-fledged ESDMA may take –at least given the current state of the craft– too much time for dealing with acute crises when they occur. However, if the necessary analytic capabilities are available, then ESDMA may be useful in tranquil periods in an ex-ante way to

- explore the robustness, flexibility, and/or resilience of *systems* or possible system designs (second line of defence) for all sorts of (fictitious) acute crises;
- scan for plausible/potential threats and ways to prevent/fight them (first line of defence).

Type II: Imminent Crises – urgent – maybe just enough time for analysis and action

Imminent crises urgently require analysis, policymaking, and development/activation of capabilities. Their occurrence is often slightly less uncertain than that of acute crises: after the first signs, it is clear that a crisis will occur, but not exactly when, nor how it will develop over time, nor with what force it will hit, nor what the cumulative impacts will be, et cetera. There is room for analysis and preventive/mitigating action (first line of defence), as well as for the development or activation of specific and generic capabilities for managing the crisis and dealing with the aftermath (third line of defence). But there is not enough time to fundamentally change the system into a robust/flexible/resilient system. Imminent crises are often slightly more dynamically complex than acute crises because of their genesis and their dynamic development (from the first sign till the last ripple) that may be influenced by policies and actions.

A good example is the 2009 pandemic flu A(H1N1)v: after the early detection of a flu outbreak in Mexico, it was very uncertain how it would develop (e.g. whether there would be one, two or more waves), how infectious and lethal this variant would be, which groups and countries would be hardest hit, whether a vaccine would be ready in time, for whom, et cetera (see subsection 4.2 and (Pruyt and Hamarat 2010b)).

Other examples include imminent economic/financial crises (such as the €/debt-crisis following the communiqué about the Greek fraud), speculative bubbles and ensuing crises, and financial/economic crises caused by interventions to remedy past crises (e.g. overly expansive monetary policies and deficit spending).Economic/financial manias are often followed by panics, crashes, and depressions (Kindleberger and Aliber 2005): manias may therefore be good indicators for imminent crises.

Especially ESDMA may be useful for imminent crises for ex-ante design of –preferably adaptive– policies that are effective (for dealing with the worst credible cases) and robust (first line of research), and related to the design of adaptive policies, the design of a monitoring system required for the adaptive policy. It may also be used to explore plausible evolutions of the imminent crisis to sharpen the understanding of possible dynamics and potential consequences in order to improve/prepare the third line of defence (crisis management).

ESD may be helpful for a first quick and dirty analysis, but facing imminent crisis, there is –at least most of the time– enough time available for deeper and broader analysis.

And if the necessary analytic capabilities are available, then ESDMA may also be useful in tranquil periods in an ex-ante way in order to:

- explore the robustness, flexibility, and/or resilience of *systems* or possible system designs (second line of defence) for all sorts of (fictitious) imminent crises;
- scan for plausible/potential imminent threats and ways to prevent/fight them (first line of defence).

Type III: Chronic Crises – not so urgent – too much time to spare...

Chronic crises are on the one hand not so urgent because their dynamics are rather slow and because they are simply not rapidly solved. They are on the other hand highly undesirable and solving them is therefore urgent too. Most chronic crises are often characterised by a high degree of uncertainty about the link between structure and behaviour, the effectiveness of (combinations of) policies, and their future dynamics, and hence, by some degree of dynamic complexity.

Examples include chronic depressions/recessions like the Japanese recession in the 1990s, poverty and unsustainable population growth (e.g. in many parts of Africa), chronic underdevelopment of bottom billion countries kept from developing by multiple traps (Collier 2008), (soft) drugs related criminality (see (Pruyt 2009a)), long lasting civil wars and international conflicts.

ESDMA may be useful in case of chronic crises for exploring the mechanisms (structures and conditions) and/or traps (feedback loop structures) that sustain chronic crises, and the uncertainties related to them and designing (combinations of) structural policies that effectively and robustly change the system and break the crisis (second and first line of defence).

Short-term crisis management is mostly not applied because ineffective in case of chronic crises, hence, there is no third line of defence. ESD may be the first step to instigate ESDMA, but ESD in isolation is not enough for dealing with uncertain chronic crises.

Type IV: Slumbering Phenomena as Potential Breeding Ground for Acute and/or Chronic Crises – uncertain urgency – maybe sudden maybe chronic, maybe next week maybe next decade. . .

Slumbering phenomena as potential breeding ground for acute and/or chronic crises are characterised by deep uncertainty about the dynamic complexities and strength and duration of plausible acute and/or chronic crises (caused by these slumbering phenomena), and also about the urgency to act. Although there is uncertainty related to the occurrence of the plausible acute and/or chronic crises, for some of these crises their occurrence is not so uncertain, but the 'when' and 'how' are.

Examples of such slumbering crises are: complex slumbering conflicts (like the Israeli-Palestinian conflict); chronic problems and potential acute conflicts related to the sharp rise in the ageing population; social-economic-political segregation/polarisation and radicalisation/extremism; criminal interference in, loss of control over, or delocalisation of critical infrastructures/enterprises; (geopolitical/local) crises related to real or artificial scarcity (oil, metals/minerals, water, food); interventions in failing states and international terrorism; climate change and geopolitical conflicts (e.g. in the arctic region).

Although ESD may be appropriate for (manual) exploration of some of the plausible scenarios and as the initial impetus for ESDMA, it is especially ESDMA that may be most useful for type-IV kind of crises. ESDMA may be useful for dealing with these slumbering crises by:

- testing the robustness/flexibility/resilience of systems or system designs (second line of defence) and designing monitoring and early detection systems for potential but unanticipated problems;
- helping to design mitigation/preventive policies to fight future crises by attacking the slumbering phenomena (which may be easier and less costly than dealing with the consequences of crises) (first line of defence);
- helping to decide about building capabilities for crisis management and adaptation (third line of defence).

4 ESD and ESDMA Applied to Some Safety/Security Issues/Crises

Some of the examples mentioned above are elaborated in the following subsections. The cases are discussed in order of decreasing order of urgency and increasing order of analytical complexity. The case dealt with in subsection 4.1 is an acute crisis and the uncertainties pertain to parameters and functions. The case discussed in subsection 4.2 is an imminent crisis and uncertainties related to parameters, formulations and boundaries of a single model are dealt with. The case in subsection 4.3 is a slumbering phenomenon that may lead to acute/chronic crises and model/structural uncertainties are dealt with.

4.1 Case I: Acute Bank Crises – The Double Run on the DSB Bank

4.1.1 Issue and Characteristics

On 1 October 2009, Pieter Lakeman publicly called for a run on the DSB Bank, a relatively small Dutch bank. The first run following Lakeman's call only lasted a few days, but it was followed by a period in which the liquidity position of the bank kept on deteriorating, until rumours and a second run finished off the bank. This particular bank crisis/failing was isolated in the sense that it did not lead to any cascading and/or systemic effects.

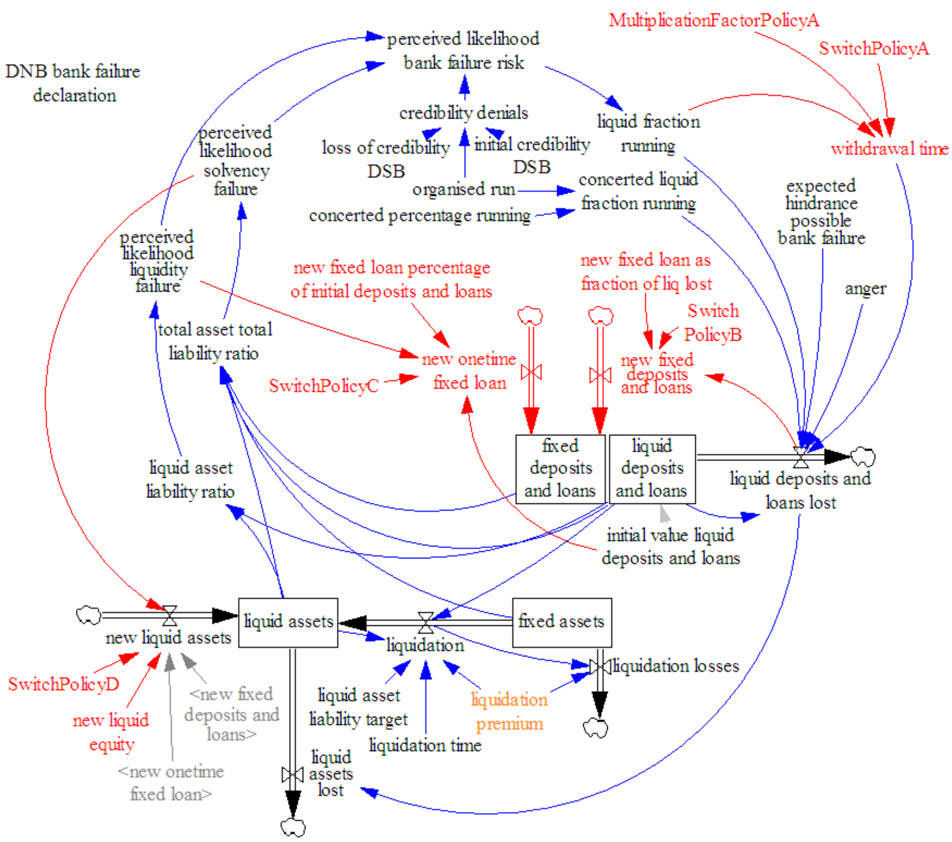


Figure 3: Aggregated structure of a 'concerted bank run' SD model (policy structures in red)

At the outbreak of this crisis, it was a typical example of an acute crisis – judging from what happened after the first concerted run on the bank, it may be argued to have turned into an imminent crisis. The initial bank run was unthought-of and therefore unexpected, although insiders knew about problems at DSB Bank. After Pieter Lakeman's call, the crisis became plausible and extremely urgent. However, it was not clear how/when the crisis would unfold – the dynamic complexity of the crisis was deeply uncertain.

An exploratory System Dynamics model of a concerted bank run was developed within hours after Pieter Lakeman's call for a run on the DSB Bank but before the development of ensuing events. This small, simple, high-level, fast-to-simulate model was used at that time for the purpose of exploration, more precisely, to quickly foster understanding about the possible mechanisms and dynamics of a concerted bank run, and to test high-level policies to prevent such concerted bank runs from succeeding[5].

4.1.2 The ESD Model and Analysis of the DSB Bank Crisis

The stock-flow diagram of the ESD model is displayed in Figure 3. Since the model was built to be a short-term crisis model, it was assumed that (i) there is no change in assets due to profit accumulation, (ii) fixed and guaranteed deposits and loans do not come at terms, (iii) there are no net shifts from liquid to fixed assets, nor from liquid to fixed deposits and loans. Note that soft –but possibly important– aspects like anger and expected hindrance from (other recent) bank failures are explicitly modelled.

[5]For more details on the DSB Bank case, see (Pruyt and Hamarat 2010a) and `http://forio.com/simulate/simulation/e.pruyt/dsb` for the sim related to the basic ESD model.

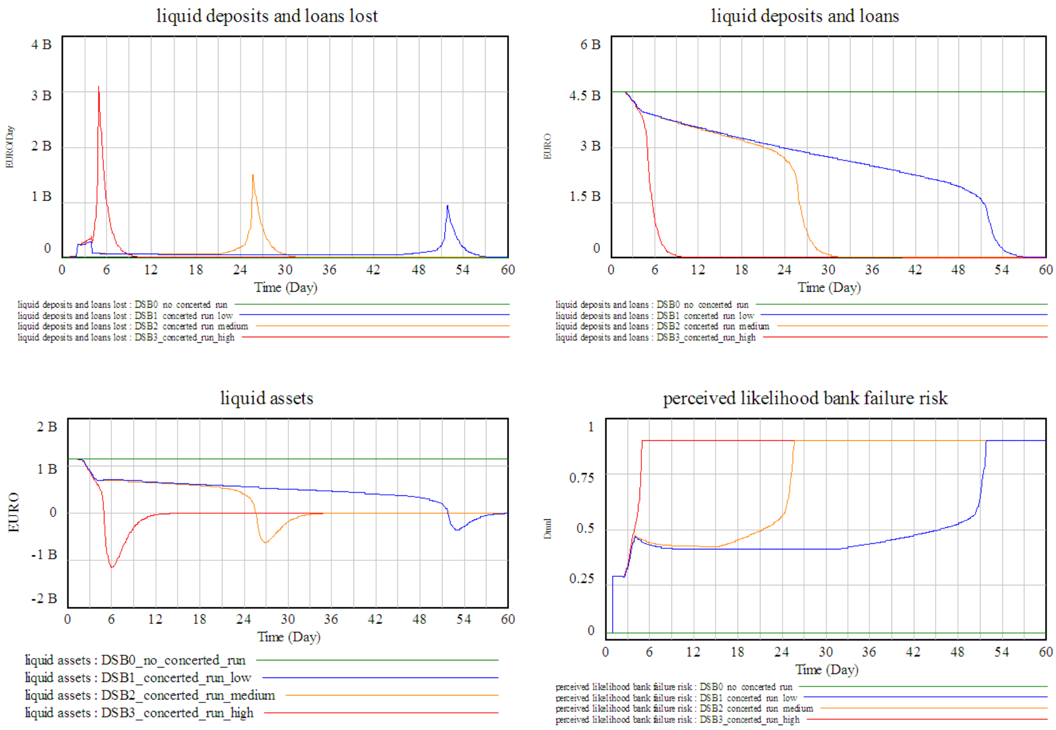


Figure 4: Behaviour of the DSB Bank model for four different scenarios

Four scenarios with somewhat different parameters were used to explore plausible behaviours. The goal of this scenario exploration was to get some feeling about the modes of behaviour that could be generated. Figure 4 shows that the modelled bank seemed to collapse sooner or later after an initial perturbation of sufficient amplitude. However, the delay with which the second run follows upon the concerted run makes a big difference from an intervention/action point of view: in scenarios DSB1 and DSB2 there seems to be some time for taking the necessary measures to strengthen the liquidity and/or solvency position, but not in scenario SDB3 in which the second run follows immediately upon the first run. In that case, automatic mechanisms have to be in place to slow the outflow of liquid deposits.

Although exact prediction of the DSB crisis was –also with this model– impossible, the ESD model made a second run foreseeable or at least thought-of/imaginable. The DSB2 run happened to be pretty close to what happened afterwards in reality.

Policies/strategies for dealing with the undesirable behaviours (in this case all scenarios but the green DSB scenario) could then be tested using ESD. However, such preliminary explorations and policy analyses are not systematic enough for issues of considerable complexity and uncertainty, and could therefore be argued not to be sufficiently reliable to base decision-making on. That is what ESDMA may be needed for.

4.1.3 The ESDMA of the DSB Bank Crisis

The next step, after building the ESD model and a quick an dirty exploratory analysis (in total about 3 hours), would be a fully-fledged ESDMA. In the DSB Bank case, an ESDMA was not performed at the time, but was performed months later, in order to develop the ESDMA multi-method and illustrate it on a relatively simple problem.

The first function of ESDMA is deep analysis. Two types of uncertainties are explored here by means of ESDMA: uncertainties related to parameter values and uncertainties related to rather

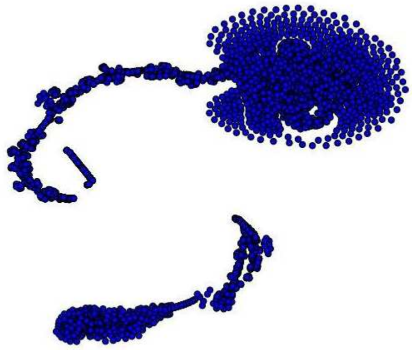


Figure 5: Resemblance plot of a sample of 5000 ESDMA trajectories

uncertain functions. The resemblance plot in Figure 5 shows that –in spite of the fact that many parametric and some structural uncertainties are varied simultaneously– there is still enough structure in the data to display the individual traces. Figure 6 shows indeed that four modes of behaviour can be distinguished.

The second –and from a policymaking perspective most important– function of ESDMA is to systematically explore the effectiveness/robustness of policies. The preliminary conclusions of the ESD are –in this case– confirmed by the ESDMA: Figure 7 shows histograms of the simulated collapses of the bank. The graph on the left hand side shows the base case in which slightly less than half of the 200.000 scenarios result in a collapse of the bank, mostly immediately or in the short run (first two weeks), or in the medium term, after continued losses of liquid deposits. The next graph (second from left) shows that a policy solely aimed at slowing the loss of liquid deposits and loans does little to prevent a second run from happening. The third graph from the left shows that a policy to make up for (a big) part of the liquid deposit and loan losses by gradually obtaining fixed deposits and loans (for example by raising the interest rate on those products) may work (if feasible in practice), but not in case of a high liquidation premium. The next graph, fourth from the left, shows that a policy in which large fixed loans are sought for dealing with the liquidity problem may work, but may nevertheless lead to a gradual loss of liquid deposits and loans. And the fifth graph from the left shows that an equity policy may help to deal with the solvency problem, but does not seem to be enough for dealing with the liquidity problem. However, that may be solved by combining the latter policy with policies to deal with acute liquidity problems, as displayed in the right hand side graph.

4.2 Case II: Imminent Health Crises – The 2009 A(H1N1)v Flu Crisis

4.2.1 Issue and Characteristics

This second case is more complex in terms of the topic, the ESD, and the ESDMA[6].

In April 2009 a new flu virus –initially called swine flu or Mexican flu, later called A(H1N1)v– was detected in Mexico and the USA. The ensuing crisis is a good example of a type II crisis: many experts foresaw, by the end of April 2009, an imminent flu epidemic/pandemic, although its characteristics and dynamics (timing, waves, consequences, et cetera) were still very uncertain and impossible to predict. It was clear that action needed to be taken urgently (since the time required to develop new vaccines and/or take other measures may well be longer than the time available for doing so).

Nations were especially concerned about the potential loss to human life, and later (after it became clear that this variant was less lethal than initially feared) about the potential disruptive

[6]See (Pruyt and Hamarat 2010b) for a full account and `http://forio.com/simulate/simulation/e.pruyt/` for the sim related to the basic ESD model.

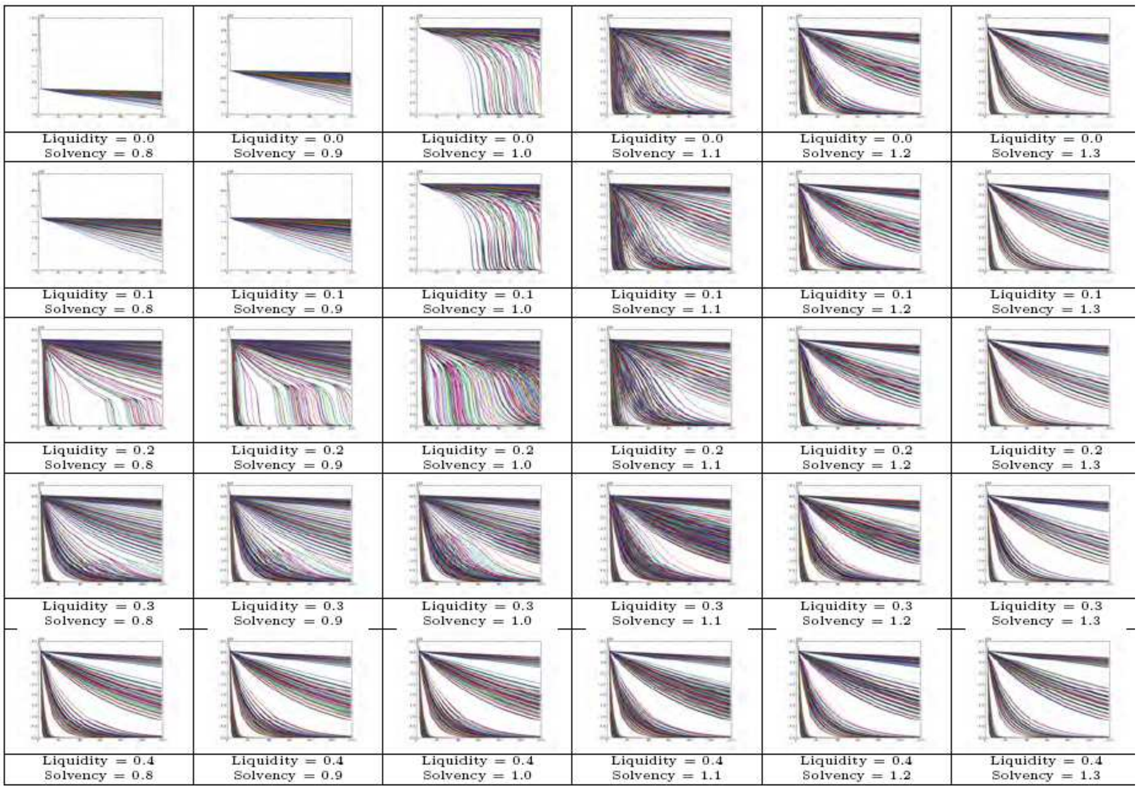


Figure 6: 48000 trajectories of the *liquid deposits and loans* in terms of the inclination points of the liquidity and solvency functions

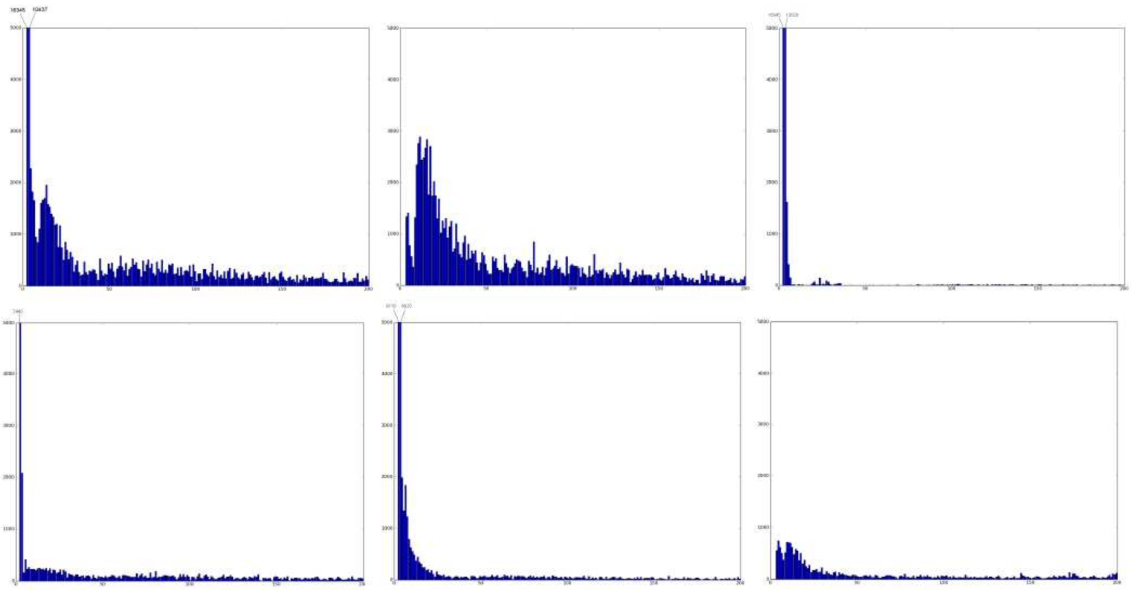


Figure 7: The effect of (from left to right) no policy, a slowing policy, a gradual fixed deposits and loans policy, a large fixed loans policy, a solvency policy, and a combined slowing and solvency policy on the collapse of the bank for 200.000 simulations over 100 days after the call

effects for health care systems, and societies/economies in case more than a third of the (active) population would be ill simultaneously.

4.2.2 Imminent Flu Epidemic/Pandemic– ESD Model and Analysis

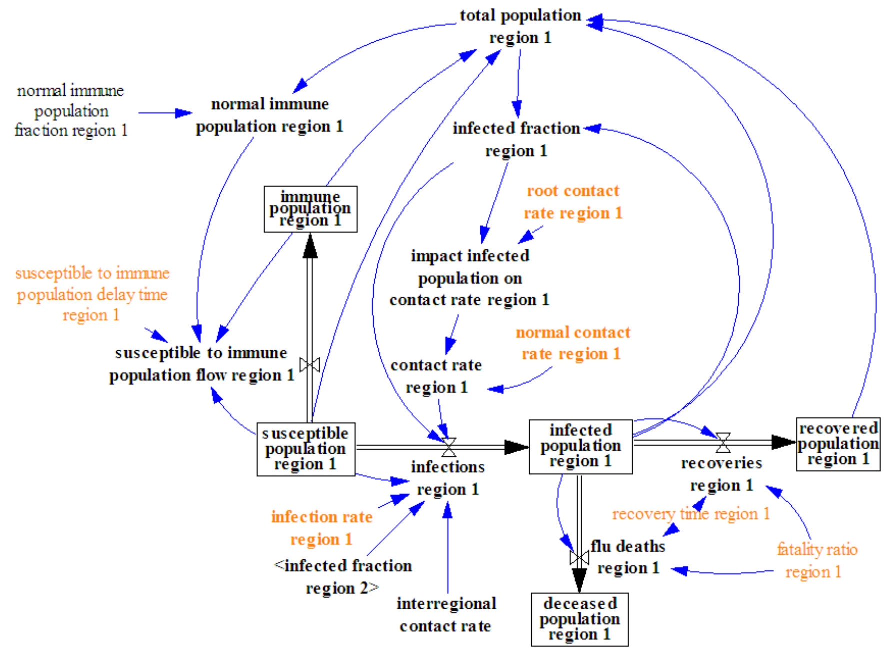


Figure 8: Stock-flow diagram of region 1 of the two-region flu model

Shortly after the WHO reported the first signs of an outbreak of a new flu variant in Mexico, little was known about the possible dynamics and consequences of a epidemic/pandemic of the new flu variant. An ESD model was developed shortly after the first signs of an outbreak were reported in order to foster understanding about the plausible dynamics of a new flu epidemic/pandemic, and to test policies for dealing with it (see Figure 8 for the stock-flow structure of one of two similar regions). The model is small, simple, high-level, exploratory, data-poor (no specific structures nor detailed data beyond crude guestimates were added), and history-poor. It was used in an ex-ante exploratory way: developments were not waited for and uncertainties were amplified and explored instead of reduced or ignored.

Figure 9 shows the behaviour of four plausible scenarios generated with rather similar parameter sets. Region 1 stands for the 'Western World' (with a population of about 600.000.000), and region 2 for the densely populated part of the 'Developing World' (with a population of about 2.000.000.000). Note that these scenarios are rather innocent compared to the '*worst* credible' scenarios discussed below. The ESD model can be used in isolation (without EMA) to get a feeling about possible plausible behaviours and the effect of some promising policies.

Sensitivity analyses show, however, that the behaviour over time may critically depend upon uncertain aspects/parameters. This is confirmed by a multivariate sensitivity analysis (LH 2000 runs) displayed in Figures 10(a) and 10(b). [Note that the individual traces in the left hand side graph are more informative than the confidence bounds, which are static distributions (at each moment in time instead of over time).] Using the same samples, it is shown in Figures 10(c) and 10(d) that the combination of social measures (to reduce the contact rate) and mass vaccination may be effective in many, but not in all cases.

Although risk analysis (LH sampling) has been used here, it does not mean that the entire uncertainty space has been explored or that the robustness of (adaptive) policies has been properly tested – hence the need for ESDMA.

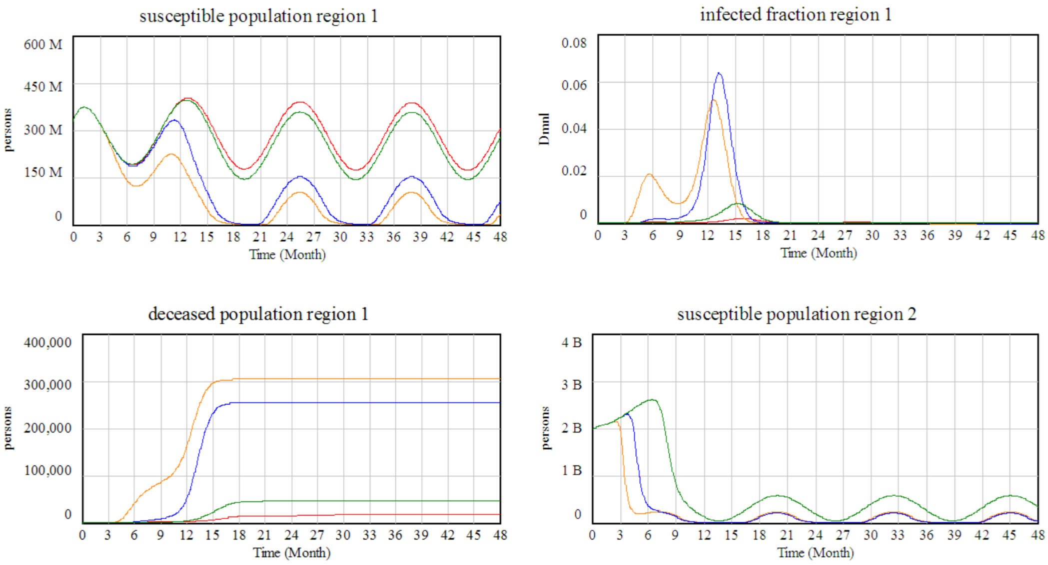
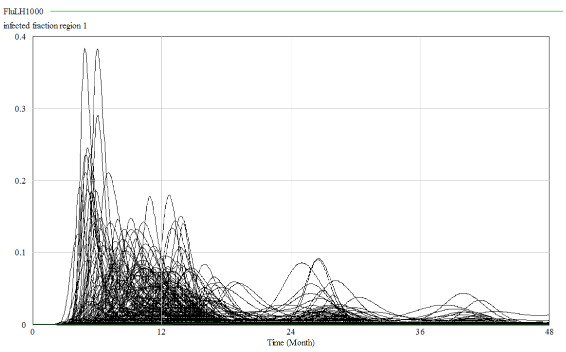
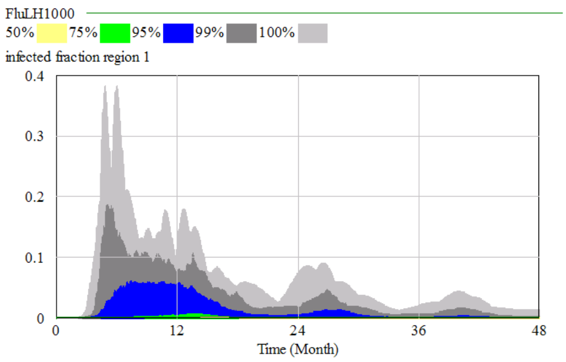


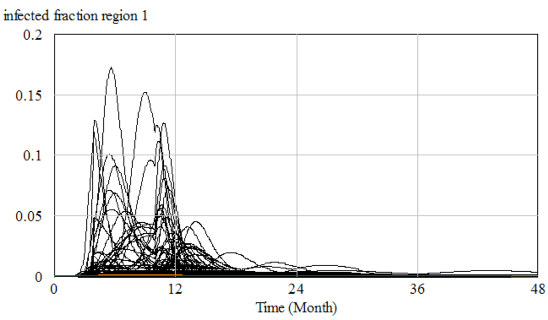
Figure 9: Behaviour of the two-region flu model for four different base case scenarios



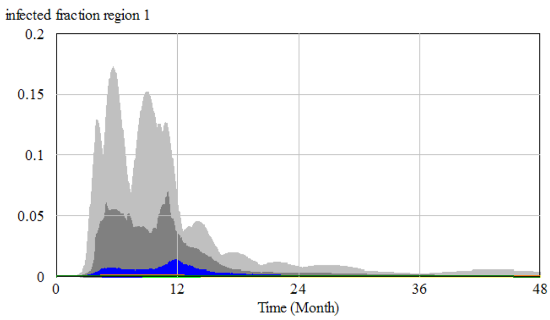
(a) 2000 individual base case runs



(b) 'Confidence intervals' for 2000 base case runs



(c) 2000 individual traces for a combination of social and vaccination policies



(d) 'Confidence interval' for a combination of social and vaccination policies

Figure 10: Risk analysis LHS2000 for the base case and a combined flu policy

4.2.3 Imminent Flu Epidemic/Pandemic– ESDMA

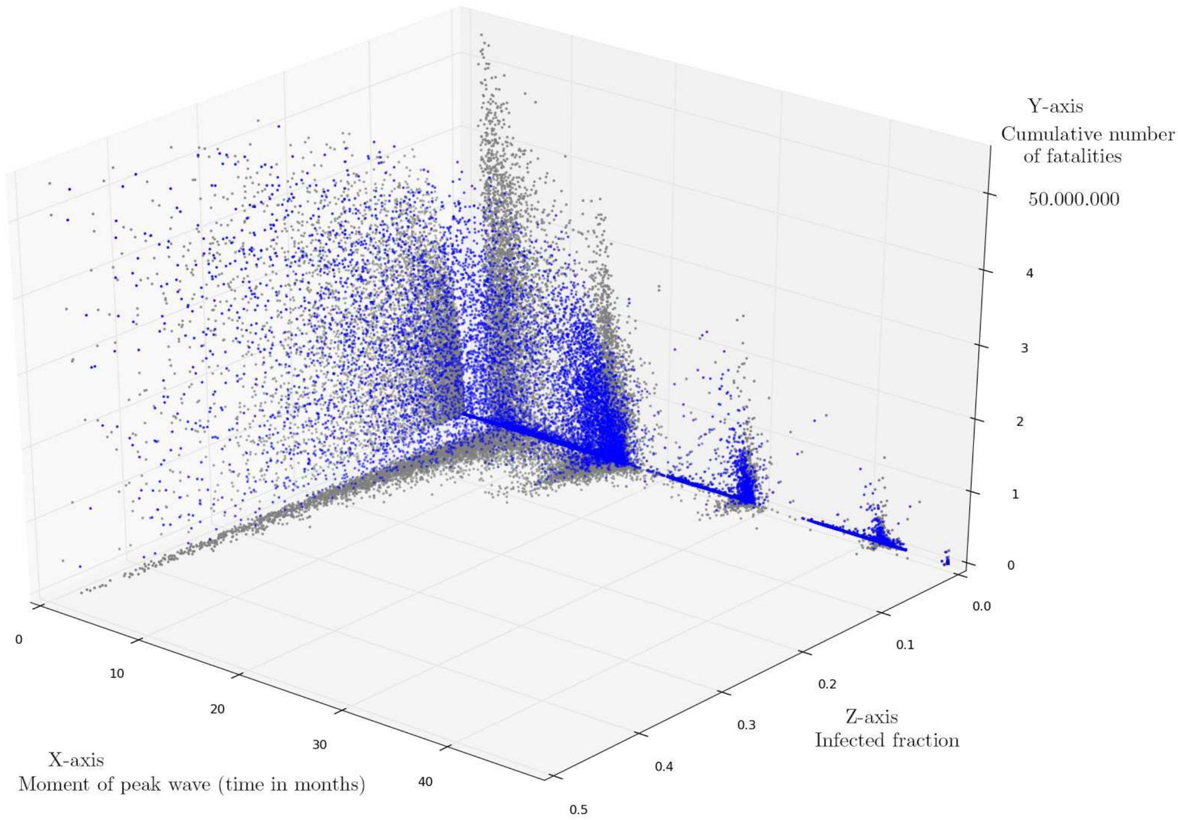
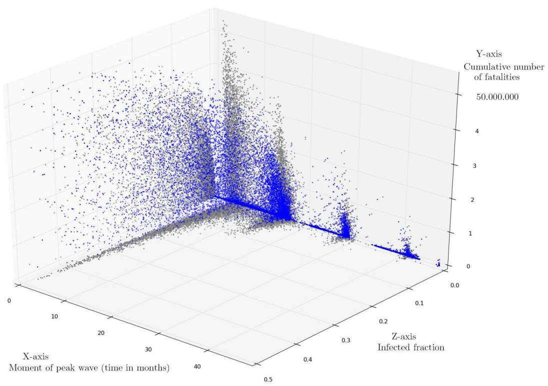


Figure 11: Scatter plot with projections of the LHS 20.000. X-axis: 0–48 months; Y-axis: 0–50% infected fraction; Z-axis: 0–50.000.000 fatal cases

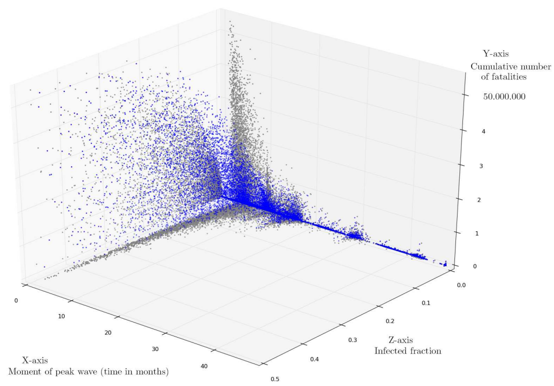
Later, the ESD model was used as a test/development case for ESDMA. Parametric and structural uncertainties (different model formulations) were systematically explored and policies tested given 17 critical uncertainties. Figure 11 shows a three dimensional plot of 20.000 (LHS) runs in terms of the highest value of the *infected fraction* (Z-axis, from 0% to 50%) to reflect the maximum societal disruption, the corresponding moment in time of the largest wave (X-axis, from month 0 to month 48), and the total cumulative number of deaths (Y-axis, between 0 and 55.000.000 fatalities). Each blue dots is one plausible flu scenario (e.g. with multiple waves). This graph shows that the most disruptive scenarios in terms of societal disruption of the Western world and number of deaths in the Western world would be those that peak during the first northern hemisphere summer (in the most catastrophic runs up to 55.000.000 fatalities on a population of 600.000.000 and an infected fraction up to 50%). Flu pandemics that only peak during the following northern hemisphere winter may (without vaccination) be somewhat less catastrophic in terms of societal disruption (infected fraction of 12%) and number of fatalities (up to 35.000.000 fatalities on a population of 600.000.000).

Since the large-scale development of vaccines takes more time than is available for the worst credible first-wave scenarios but less time than is available for slightly less catastrophic second-wave scenarios, it is rather tempting to conclude that both adaptive vaccination and adaptive social distancing policies are needed. A sufficient initial order with an option to order more if necessary – preferably from a coalition of cooperating nations– would then lead to the development of vaccines and the start up of production to satisfy the amount initially ordered, and a second amount –

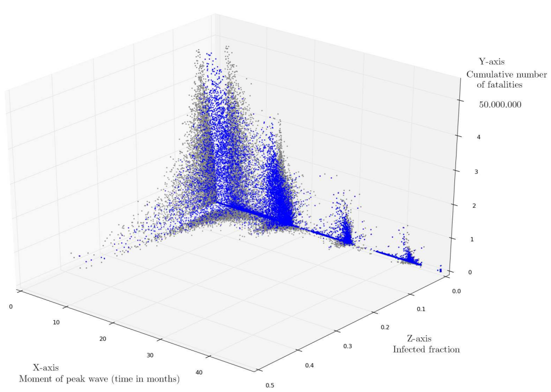
informed by monitoring of fatality rates, infectivity rates, immunity, et cetera– could be ordered once development is under way and/or production is starting up (Pruyt and Hamarat 2010b).



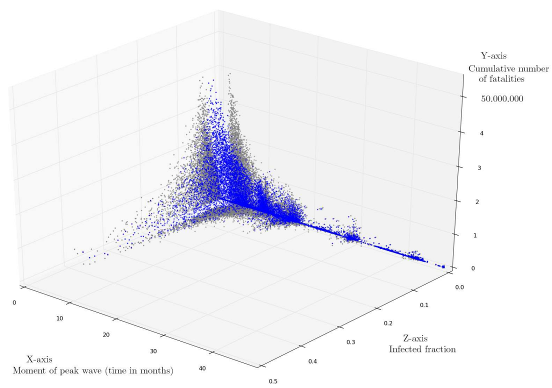
(a) No Policy



(b) Adaptive Policy 1: vaccination based on the fatality ratio



(c) Adaptive Policy 2a: social distancing based on monitoring of infected fraction



(d) Policy 3

Figure 12: No policy versus (inexpensive) adaptive policies on the LHS20000 ensemble

It is shown in (Pruyt and Hamarat 2010b) that adaptive policies are better and cheaper than static policies and it can be argued that they are better than ad-hoc policymaking which suffers from potentially detrimental delays.

Starting from the no-policy case (top-left) in Figure 12, it seems possible to devise adaptive vaccination policies[7] reduce the number of catastrophic outbreaks after the vaccination campaign (top-right). However, no matter how robust the vaccination policy, it does not help to contain the most catastrophic waves in the first summer (here 2009). Adaptive social distancing policies (bottom-left) may help to reduce the societal/economic disruption of flu outbreaks (in terms of infected fraction), as well as catastrophic numbers of fatalities. Combining both pre-specified policies (policy 3 – bottom-right) does not entirely/robustly solve the problem for all scenarios. Adaptive anti-viral policies and hospitalisation policies may need to be added to both adaptive policies discussed here (but that is not investigated here). Another option to robustly reduce the threat of a catastrophic pandemic (which was tested successfully) would be the design of much stronger (and consequently also much more expensive) adaptive policies.

[7]Adaptive policies are pre-specified policies that are automatically activated and varied in strength based on monitoring of the situation – similar to real options based on monitoring of the latest information available.

4.3 Case III: Plausible Mineral/Metal Scarcity Crises

4.3.1 Issue and Characteristics

Possible mineral/metal scarcity gets ever more attention as a potential security threat and a challenge for civil protection (Kooroshy et al. 2010). Not only may shortening 'years of extraction until exhaustion' of high-volume minerals/metals pose a threat to the (current) 'modern' way of living, potential strategic/speculative behaviour with regard to rare earth metals may also hinder or block the (further) development of modern societies towards more sustainable ones. These rare earth metals seem to be required in ever bigger quantities for many innovative –mostly 'greener'– technologies such as hybrid cars, flat screens, solar cells, led lamps, mobile phones. But these minerals are quite dispersed, and their extraction expensive. Moreover, countries like China, which have quasi-monopolies on the extraction of specific rare earth metals, are believed/feared to constrain (future) exports. Hence, it is important to assess whether these natural and/or artificial constraints may actually lead to temporary and/or structural scarcity, which may, in turn, hinder the transition of our society towards a more sustainable one.

Possible future mineral/metal scarcity problems are typical type IV problems since such crises can be acute and chronic, and are just manifestations of underlying slumbering phenomena. This issue is discussed at length in (Pruyt 2010).

4.3.2 Plausible Mineral/Metal Scarcity – ESD Model and Analysis

The generic ESD model developed for this issue is relatively simple (see Figure 13). The ESD model can easily be turned into specific models for specific issues. In this case, the ESD model was used in its generic form to reflect about plausible worst credible scenarios. In order to do so, assumptions about underlying phenomena were gradually worsened (see Figure 14). The scenario started from a 'low growth scenario' resulting in small and temporary shortages and some chronic scarcity in the longer run (see Figures 14(c) and 14(d)). The crises become somewhat more problematic in case of high(er) growth rates (see Figures 14(e) and 14(f)). Six further steps –after subsequently increasing the energy intensity of extraction, increasing the price substitute, decreasing the price elasticity of demand, gradually quadrupling energy prices, and adding demand growth cycles and energy cost cycles– resulted in the worst credible scenario in Figures (14(g) and 14(h)): short to medium term scarcity (and market price swings) turn into long-term chronic scarcity.

However, these scenarios and corresponding graphs are not to be interpreted as 'predictions' about the size and timing of the shortages and price spikes, etc[8]. These scenarios are just plausible modes of behaviour.

[8] The simulation start time does not coincide with the year 2010 in order to break any predictive interpretation.

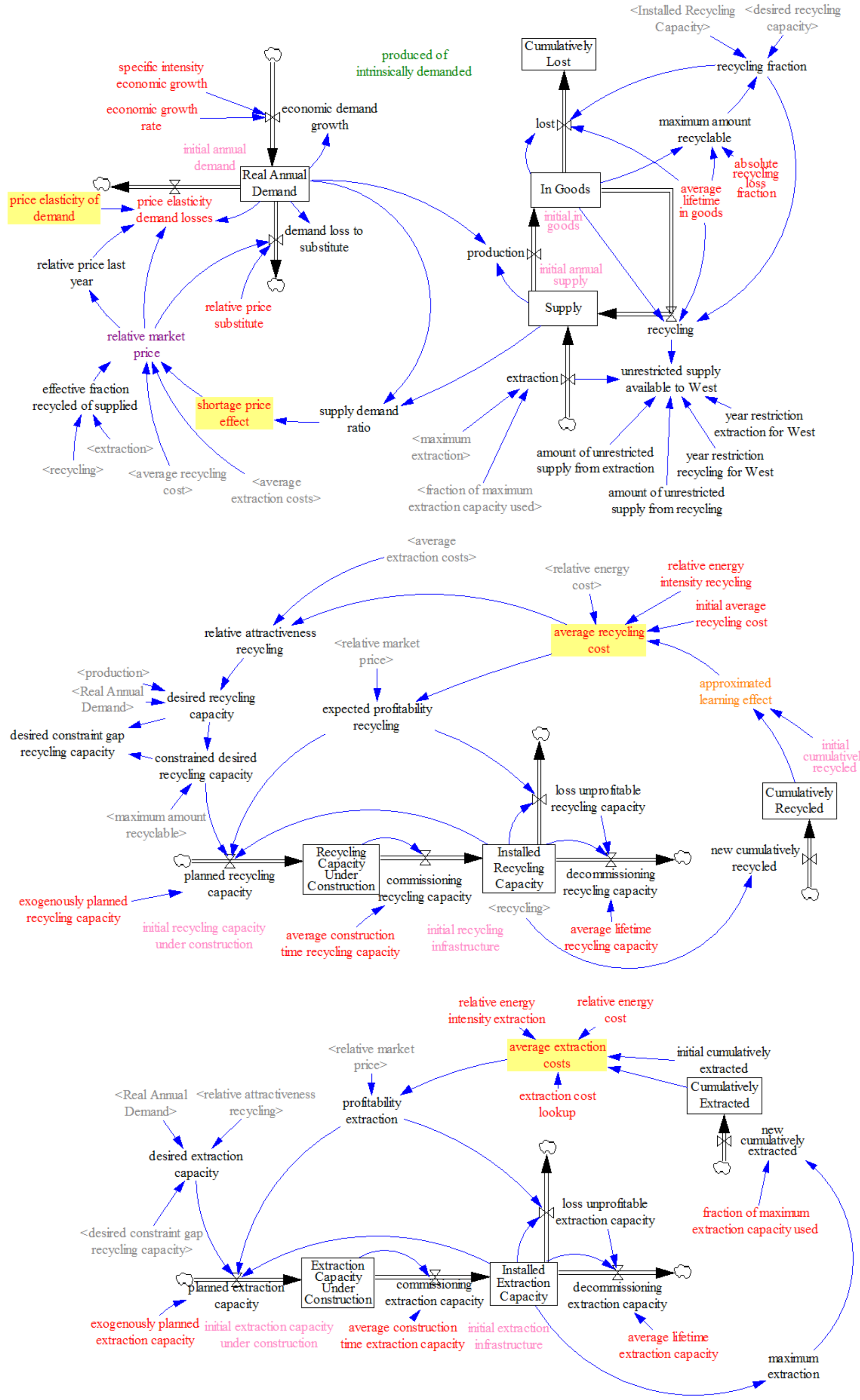
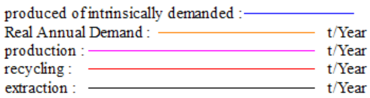
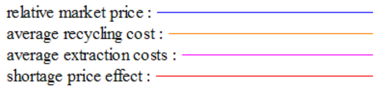


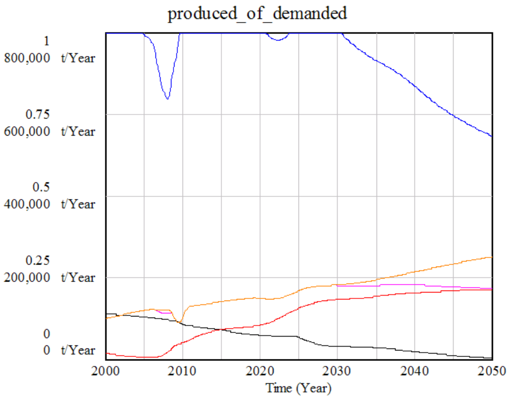
Figure 13: SFD of the three submodels of the generic ESD model – Top: demand, supply and price; Middle: installed recycling capacity; Bottom: installed extraction capacity



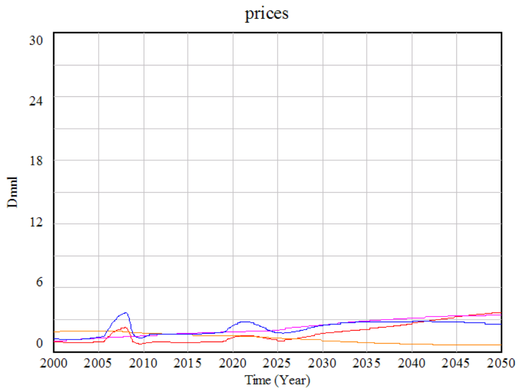
(a) Legend left hand side graphs



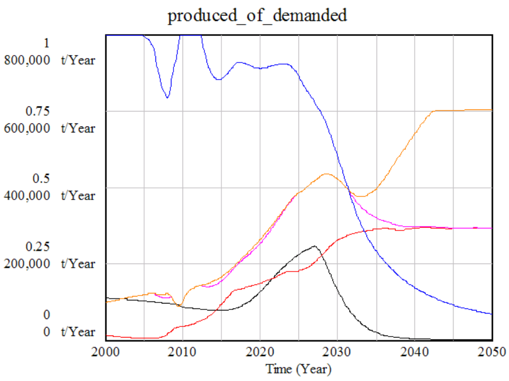
(b) Legend right hand side graphs



(c) Scenario 1: low growth scenario

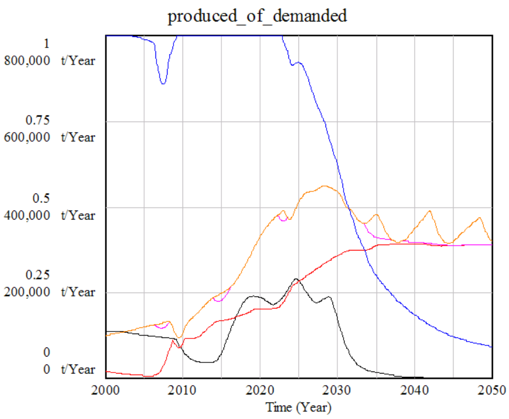


(d) Scenario 1: low growth scenario

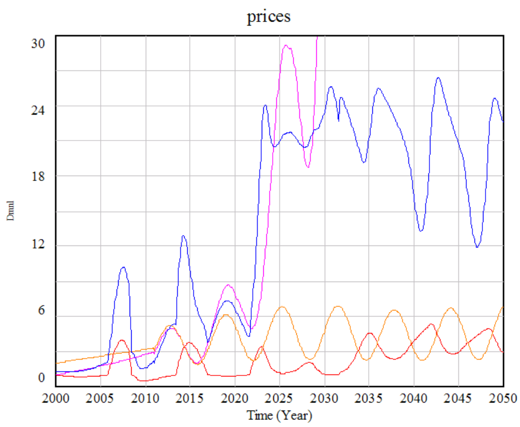


(e) Scenario 2: high growth scenario

(f) Scenario 2: high growth scenario



(g) Scenario 8: scenario 7 + sinus on demand growth and energy costs



(h) Scenario 8: scenario 7 + sinus on demand growth and energy costs

Figure 14: Scenarios 1, 2, and 'worst credible' scenario 8

5 Concluding Remarks, Lessons Learned, Future Work

ESD models may be useful to quickly explore complex issues, generate plausible behaviours, and test whether structural/parametric uncertainty matters or not. However, ESD is not appropriate for systematic exploration and testing of policy robustness in the face of deep uncertainty. ESDMA allows to systematically explore uncertainties and –more importantly– test the robustness of policies under deep uncertainty. However, ESDMA is currently still time-consuming.

Although it may be impossible in ESDMA of complex systems to grasp all combinations of uncertainties explored, policy recommendations may actually be easier to understand ('this or that policy/strategy is more effective and robust over this uncertainty space') and more valid: although no single exploratory model formulation and parameter set may in the end be right, it could be argued that the conclusions of an ESDMA are more robust than those of a single model formulation and parameter set.

ESD and ESDMA may be useful in different ways for different kinds of crises:

- For acute crises, ESD (and ESDMA) may be used in order to quickly explore plausible scenarios and test the effectiveness of policies for particular families of scenarios.
- For imminent crises, ESD may be used to explore the urgency and get a first impression of plausible scenarios and promising policies, and ESDMA may be used to explore and analyse the uncertainty space and test the robustness of promising policies to deal wtih undesirable scenarios.
- For chronic crises, ESDMA may be used to analyse how to get out of them without further deterioration. In case of chronic crises, more time for analysis should be made available. Although they ought to be solved as soon as possible, but they are really hard to solve.
- For slumbering crises, ESD may be used to support 'scenario reflection' processes, and ESDMA may be used to analyse and explore the full uncertainty space and robustness of promising policies.

There is a clear trade-off between ESD and ESDMA in terms of the speed of execution and the exploration of deep uncertainty: performing an ESD can be done quickly (hours to days) but the exploration of deep uncertainty is insufficient for decision-making whereas performing an ESDMA takes much more time (days to weeks) but the exploration of deep uncertainty should be sufficient for decision-making. The urgency of the matter is therefore a decisive criterion for choosing between ESD and ESDMA.

The ESD, EMA and ESDMA approaches may be relevant for other scientific disciplines dealing with complex issues under deep uncertainty, especially for policymaking, through the development of:

- insights about underlying mechanisms, (inter)actions, and conditions, and their power to generate potentially disruptive dynamics;
- simulation models and (online) games to explore and learn from 'virtual' crises,
- insights about the effectiveness and robustness (and potential side-effects and risks) of designs/policies/regulations/early warning systems.

In the near future, our team will work on cases of increasing complexity in order to gradually advance our work on ESDMA. Until now, we mostly explored uncertainty ranges, different formulations/functions, and (slightly) different models. Simple analysis and visualisation techniques were mostly good enough because the behaviours generated with the different variants of the exploratory models were sufficiently distinctive. In future research, we will simultaneously explore broad ranges, functions, boundaries –in other words (very) different model formulations– as well as different world views with very different models and preferences. Each of these steps will lead

–at first sight and without decent analyses and visualisation techniques– to more and more chaotic behaviours and ensembles. We will therefore also explore better ways to deal with problems of combinatorial complexity, and develop better and more user-friendly methods, techniques, and tools, starting from existing analysis methods, data mining techniques, mathematical and control theory techniques, formal modelling methods, and multi-dimensional visualisation techniques.

Acknowledgements

I am greatly indebted to Caner Hamarat for performing ESDMA on several of my ESD models and for generating Figures 6, 7, and 11. Our ESDMA team also owes much gratitude to Jan Kwakkel for his seminal work on EMA, for the many discussions about deep uncertainty, and for generating Figure 5. I would like to thank the National Risk Assessment Methodology group of the Dutch Ministry of the Interior and Kingdom Relations for the fertile discussions regarding different types of crises. Finally, I would like to thank Emmanuel Phelut for our discussion about model use that instigated the writing of this paper.

References

Agusdinata, D. (2008). *Exploratory Modeling and Analysis. A Promising Method to Deal with Deep Uncertainty.* Phd dissertation, Delft University of Technology, Delft. `http://www.nextgenerationinfrastructures.eu/index.php?pageID=17&itemID=433706`. 3, 6

Agusdinata, D., J. Van der Pas, W. Walker, and V. Marchau (2009). An innovative multi-criteria analysis approach for evaluating the impacts of intelligent speed adaptation. *Journal of Advanced Transport systems 43*(4), 413–454. 6

Bankes, S. (1993, May-June). Exploratory modeling for policy analysis. *Operations Research 41*(3), 435–449. 6

Bankes, S., W. Walker, and J. Kwakkel (2010). *Encyclopedia of OR* (upcoming 3th edition ed.)., Chapter Exploratory Modeling and Analysis. Boston: Kluwer Academic Publishers. [forthcoming]. 7

Bergmans, H., J. van der Horst, L. Janssen, E. Pruyt, et al. (2009, October). Working with scenarios, risk assessment and capabilities in the national safety and security strategy of the netherlands. Technical report, Ministerie van Binnenlandse Zaken en Koninkrijkrelaties, The Hague. `http://www.minbzk.nl/aspx/download.aspx?file=/contents/pages/102316/nlmethodforriskassessmentandcapabilityanalysing2009.pdf`. 1

Bryant, B. and R. Lempert (2009). Thinking inside the box: A participatory, computer-assisted approach to scenario discovery. *Technological Forecasting and Social Change 77*(2010), 34–49. 6

Collier, P. (2008). *The Bottom Billion. Why the poorest countries are failing and what can be done about it.* OUP Oxford. 9

Ford, A. (1999). *Modeling the environment: an introduction to system dynamics models of environmental systems.* Washington (D.C.): Island Press. 5

Forrester, J. (1968). *Principles of Systems.* Cambridge, MA: Wright-Allen Press, Inc. 5

Kindleberger, C. and R. Aliber (2005). *Manias, Panics, and Crashes: A History of Financial Crises* (5th ed.). Hoboken, New Jersey: Wiley and Sons. 9

Kooroshy, J. et al. (2010, January). Scarcity of minerals: A strategic security issue. Technical Report 02/01/20, The Hague Center for Strategic Studies, The Hague. `http://hcss.nl/en/news/1286/Scarcity-of-Minerals.html`. 19

Kwakkel, J., W. Walker, and V. Marchau (2010a). Assessing the efficacy of adaptive airport strategic planning: Results from computational experiments. *Transport Policy*. (accepted with revisions). 7

Kwakkel, J., W. Walker, and V. Marchau (2010b, 15-17 April 2010). From predictive modeling to exploratory modeling: How to use non-predictive models for decisionmaking under deep uncertainty. In *Proceedings of the 25th Mini-EURO Conference on Uncertainty and Robustness in Planning and Decision Making (URPDM2010)*, Portugal. University of Coimbra. 7

Lane, D. (2001a). Rerum cognoscere causas: Part I – How do the ideas of system dynamics relate to traditional social theories and the voluntarism/determinism debate? *System Dynamics Review 17*(2), 97–118. 5

Lane, D. (2001b). Rerum cognoscere causas. Part II – Opportunities generated by the agency/structure debate and suggestions for clarifying the social theoretic position of system dynamics. *System Dynamics Review 17*(4), 293–309. 5

Lempert, R., D. Groves, S. Popper, and S. Bankes (2006, April). A general, analytic method for generating robust strategies and narrative scenarios. *Management Science 52*(4), 514–528. 6

Lempert, R., S. Popper, and S. Bankes (2003). Shaping the next one hundred years: New methods for quantitative, long-term policy analysis. RAND report MR-1626, The RAND Pardee Center, Santa Monica, CA. 2, 3, 6

Lempert, R. and M. Schlesinger (2000, June). Robust strategies for abating climate change. *Climatic Change 45*(3–4), 387–401. 6

Meadows, D. and J. Robinson (1985). *The Electronic Oracle. Computer Models and Social Decisions*. Chichester: John Wiley & Sons. 4, 5

Pruyt, E. (2006). What is System Dynamics? A paradigmatic inquiry. In *Proceedings of the 2006 Conference of the System Dynamics Society*, Nijmegen. System Dynamics Society. `http://www.systemdynamics.org/conferences/2006/proceed/papers/PRUYT177.pdf`. 5

Pruyt, E. (2007). Dealing with uncertainties? Combining System Dynamics with Multiple Criteria Decision Analysis or with Exploratory Modelling. In *Proceedings of the 25th International Conference of the System Dynamics Society*, Boston, MA, USA. System Dynamics Society. `http://www.systemdynamics.org/conferences/2007/proceed/papers/PRUYT386.pdf`. 3

Pruyt, E. (2009a, July). The Dutch soft drugs debate: A qualitative System Dynamics analysis. In *Proceedings of the 27th International Conference of the System Dynamics Society*, Albuquerque, USA. System Dynamics Society. `http://www.systemdynamics.org/conferences/2009/proceed/papers/P1356.pdf`. 9

Pruyt, E. (2009b, July). Saving a Bank? The Case of the Fortis Bank. In *Proceedings of the 27th International Conference of the System Dynamics Society*, Albuquerque, USA. System Dynamics Society. `http://www.systemdynamics.org/conferences/2009/proceed/papers/P1273.pdf`. 3

Pruyt, E. (2010). Scarcity of minerals and metals: A generic exploratory system dynamics model. In *Proceedings of the 28th International Conference of the System Dynamics Society*, Seoul, Korea. System Dynamics Society. `http://www.systemdynamics.org/cgi-bin/sdsweb?P1268+0`. 6, 19

Pruyt, E. and C. Hamarat (2010a). The concerted run on the DSB Bank: An Exploratory System Dynamics Approach. In *Proceedings of the 28th International Conference of the System Dynamics Society*, Seoul, Korea. System Dynamics Society. `http://www.systemdynamics.org/cgi-bin/sdsweb?P1027+0`. 6, 11

Pruyt, E. and C. Hamarat (2010b). The Influenza A(H1N1)v Pandemic: An Exploratory System Dynamics Approach. In *Proceedings of the 28th International Conference of the System Dynamics Society*, Seoul, Korea. System Dynamics Society. `http://www.systemdynamics.org/cgi-bin/sdsweb?P1389+0`. 6, 9, 13, 18

Pruyt, E. and D. Wijnmalen (2010). The Dutch National Risk Assessment: An integrated multi-criteria application. *Lecture Notes in Economics and Mathematical Systems: Multiple Criteria Decision Making for Sustainable Energy and Transportation Systems 634*, 133–143. http://www.springerlink.com/content/l60t423960560140/. 1

Rademaker, M. (2008). National Security Strategy of the Netherlands: An Innovative Approach. *Information and Security 23*(1), 51–61. http://infosec.procon.bg/v23/Rademaker.pdf. 1

Senge, P. (1990). *The fifth discipline: the art and practice of the learning organization.* London. 424 p. 2

Sterman, J. (2000). *Business dynamics: systems thinking and modeling for a complex world.* Irwin/McGraw-Hill: Boston. 5

Sterman, J. (2002a). The 2001 Jay W. Forrester Award. *System Dynamics Review 18*(1), 71–72. 2

Sterman, J. (2002b). All models are wrong: reflections on becoming a systems scientist. *System Dynamics Review 18*(4), 501–531. 6

Van der Pas, J., D. Agusdinata, W. Walker, and V. Marchau (2007). Exploratory modelling to support multi-criteria analysis to cope with the uncertainties in implementing isa. In R. I. of Highway Ministry of Communications (Ed.), *14th World Congress on Intelligent Transport Systems, ITS For a Better Life*, Volume ISBN: 978-7-900209-44-3, Beijing. 6

Van der Pas, J., D. Agusdinata, W. Walker, and V. Marchau (2008). Developing robust intelligent speed adaption policies within a multi-stakeholder context: An application of exploratory modelling. In P. Herder, P. Heijnen, and A. Nauta (Eds.), *IEEE – NGInfra Scientific Conference 2008: Building Networks for a Brighter Future*, Delft. 6

Walker, W. and V. Marchau (2003). Dealing with uncertainty in policy analysis, and policy-making. *Integrated Assessment 4*(1), 1–4. 6