Catastrophe Archetypes – Using System Dynamics to Build an Integrated Systemic Theory of Catastrophes

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Abstract
We propose an Integrated Systemic Theory of Catastrophes (ISTC) using System Dynamics to model and to understand common systemic structures and behaviours of catastrophes. Current catastrophe research concentrates on a specific field and does not capture complex multi-field catastrophe scenarios that cannot be reduced to a single scientific field. For example, when looking at famines the elements of the relevant feedback loops belong to different fields of science (climate, precipitation, soil conditions, population density etc.) and no single of these sciences alone can identify the systemic structure generating famines. In this paper we introduce the concept of Catastrophe Archetypes that function as a central element of the ISTC. Catastrophe Archetypes describe systemic structures responsible for catastrophes to occur and make underlying catastrophe dynamics visible that are normally not directly seen. Within the ISTC the Catastrophe Archetypes will be used as diagnostic-, planning-, and theory building tools to explore catastrophes systemically.

Keywords
Catastrophe, Disaster, System Dynamics, System Archetypes, Catastrophe Archetypes, Systems Theory

INTRODUCTION

Catastrophes fascinate humans as they clearly show them the limits of their own existence. Almost on a daily basis media report about catastrophic events reaching from personal distress and small-scale local disasters up to large-area infrastructure destructions. The inflationary use of the term catastrophe might sometimes mislead

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outside spectators to dullness or languidness. This is all the more the case as the total number of catastrophes, their ramifications and aggregated detriments is worldwide increasing. Main reason for the increase is due to socio-economic changes (IPCC 2007, Stern 2006). Major catastrophes take place in densely populated areas that are growing fast because of ongoing population growth and urbanization. Furthermore, industrial countries have widespread and complex infrastructures and transportation ways that are highly susceptible. Over and above, climate change is assumed to be responsible for the rise of natural catastrophes such as droughts, storms and floods.

However, the apparent increase of negative headlines should not mislead to the assumption that emergency management is unsuccessful. Due to better techniques and advanced practices, catastrophes that before would have occurred can be prevented to some extent. Yet we have to consider that beyond the limits of technological measures against catastrophes new catastrophes may emerge, which have lower probability but an intensified destructive power (Lapp and Ossimitz 2006, Mrotzek et al. 2007). Thus, we are confronted with a world of increasing catastrophe potential.

Typically, catastrophe hazards tend to reach across an increasing number of scientific fields the bigger they become. The Chernobyl nuclear power plant disaster can be seen initially as a catastrophic mismanagement of a security check within Reactor 4 which led to a catastrophic failure of a technical system. With the spread of the nuclear radiation the incident became a catastrophe of the environment, the health of millions of people, the economy of wide regions and ultimately even one of the political system of the USSR (Dörner 1989, Salge and Milling 2006).

This cross-disciplinary character of catastrophes requires an approach that understands catastrophes as a systemic cross-disciplinary phenomenon. Our aim is to build an unique and truly innovative tool for the exploration of the systemic structure of catastrophes: the *Catastrophe Archetypes*. We will use them for designing an Integrated Systemic Theory of Catastrophes (ISTC).

STATUS QUO ON EXISTING CATASTROPHE RESEACH

Specific Catastrophes

In traditional catastrophe research scientists deal just with special types of catastrophes. For example seismologists give their attention to the scientific study of earthquakes and the propagation of seismic waves through the earth, but not on the study of social and economical implications of earthquakes. Their concern is to find precise knowledge about the particular catastrophe, yet without taking the general systemic catastrophe structure into consideration. In many cases quantitative simulations models with often highly specialized techniques are used. Examples of research areas that concentrate exclusively on catastrophes applying to some specific scientific field are: volcanic eruptions, storms, epidemics, avalanches, earthquakes, crash of stock markets, famines, etc.

Catastrophes as Extreme Events

To regard catastrophes as extreme events is the theoretical paradigm of the „Integrated Modeling Environment"-program at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg (Austria) (e.g. Ermolieva et al. 2003). This concept states that extreme phenomena (for example storms) have catastrophic implications. A crucial issue is to distinguish the catastrophic extreme case from the normal case and to understand the risks and consequences of extreme incidents. Looking at catastrophes as extreme events is also the approach used at the Institute for Transport and Economics at the University of Dresden, in order to analyze cascade-like spreading of catastrophes (Helbing, Ammoser and Kuehnert 2005).

Cross-disciplinary Catastrophe Theories

***Sociological Catastrophe Theory*:** Cross-disciplinary approaches to build generic scientific theories of catastrophes are few. One is the sociology of disasters, a special branch of sociology which attempts to build a sociological theory of catastrophes (Rodriguez et al. 2006, Perry and Quarantelli 2005, Artus 2005). Especially in Germany a sociological catastrophe research branch developed under the lead of Lars Clausen and Wolf Dombrowsky from the Disaster Research Center at the University of Kiel. Their research is concerned with the sociological characterization of catastrophes (e.g. FAKKEL-Modell, Kieler-Würfel) (Clausen et al. 2003). However, the sociological catastrophe approach is focused explicitly to extremely accelerated social systems.

***Mathematical Catastrophe Theory*:** Another theory of catastrophes, which is not related to specific empirical catastrophes, is the mathematical Catastrophe Theory (Thom 1975). The core of the mathematical Catastrophe Theory is a classification of different types of bifurcations (discontinuities) in systems when continuously varying a few control parameters. Although some authors speculate about associations between mathematical Catastrophe Theory and abrupt management changes, the mathematical Catastrophe Theory can hardly help to build a general understanding of catastrophes.

***Statistics of Disaster Damages*:** Another important cross-disciplinary view on catastrophes is the classification and the monetary quantification of damages caused by catastrophes, generally done by economists and/or insurance companies (Dacy and Kunreuther 1969, Okuyama and Chang 2004, MunichRe-Homepage).

***Systemic Approach to Catastrophes*:** In the course of the development of the Integrated Systemic Theory of Catastrophes (ISTC) a systemic approach to catastrophes has been developed (Ossimitz and Lapp 2006b). Catastrophes are seen as structural breakings and fundamental changes of systems. Especially the dimension *time* plays a crucial role in this theory. This makes the System Dynamics method a candidate for modeling the theoretical Catastrophe Archetypes of ISTC.

It is possible to associate different types of catastrophes with specific patterns over time. Figure 1 displays four patterns of how catastrophe scenarios can develop over time. The curve in Figure 1a shows a creeping and irreversible catastrophe, as it is the case for the deforestation of the Easter Islands (Sterman 2000). Figure 1b shows a temporary "overflow" catastrophe, like a river flooding temporarily some surrounding land (Lapp and Ossimitz 2006, Mrotzek et al. 2007). The curve in Figure 1c displays a reversible

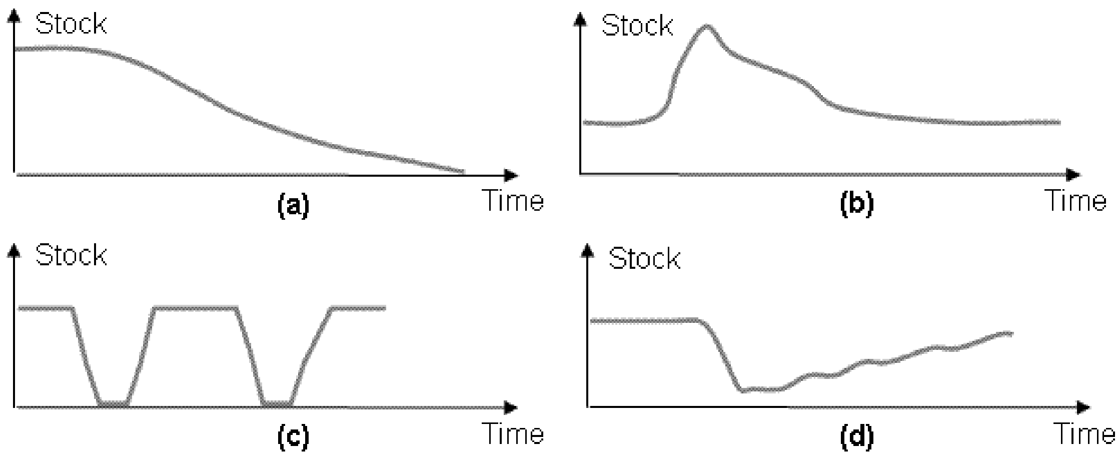

Figure 1: Role of time in catastrophe

catastrophe happening periodically, e.g. a tree loosing its leaves each autumn and regaining it next spring. Figure 1d illustrates a stable system in which a catastrophe takes suddenly place by a substantial reduction of the stock. Thereafter, it takes a long period of time to get back to the initial state. An example for this type of time behavior is the course of an epidemic in a population.

Existing System Dynamics Catastrophe Research

For a multitude of fields there exist specific System Dynamics (Forrester 1961) catastrophe scenario models, e. g. for

- Floods: Simonovic and Fahmy (1999), Ahmad and Simonovic (2000, 2004);
- Epidemics: Sterman (2000); Glass-Husain (1991); Su et al. (1992).

Most catastrophe-related System Dynamics models concentrate on showing the dynamical behavior of some special catastrophe type. A large assortment of generic System Dynamics models that may have catastrophic tendencies can be found in Bossel's "System-Zoo"-series (2004a, 2004b, 2004c).

ISTC AND CATASTROPHE ARCHETYPES

Aim of the Integrated Systemic Theory of Catastrophes (ISTC)

The ISTC will be useful to understand systemic structures and behavior of catastrophes beyond the catastrophe research done in specific fields and the existing cross-disciplinary approaches. A central research task is to identify a set of Catastrophe Archetypes which should function as a core concept within the ISTC. We suppose that the general system archetypes concept as defined by Senge (1990, 1994) can be used as a model pattern for Catastrophe Archetypes. The Catastrophe Archetypes will be derived through analyzing different catastrophe scenarios and their generic patterns in order to find catastrophe-oriented "systems archetypes".

Another important hypothesis is that Catastrophe Archetypes help to explore complex "multi-field" catastrophe scenarios which cannot be reduced to a single scientific field.

For example, when looking at adiposity (human overweight illness), one finds that the elements of the relevant feedback loops belong to different fields of sciences (medicine, agriculture, cultural science, social science, business science, etc.). None of these sciences alone can identify the systemic structure generating adiposity as a mass problem in developed countries. Also “traditional” catastrophe scenarios typically cannot be associated with just a single field of science, as already discussed for the Chernobyl accident.

Applicability of Catastrophe Archetypes

Catastrophe Archetypes can function for different purposes. They are tools for diagnostic purposes, planning or theory building.

Diagnostic: Catastrophe Archetypes provide a set of systemic structures that can be used to diagnose the catastrophe potential of situations. With this tool the situation can be monitored and possible leverage points to change the existing system structure to a desired structure can be identified.

Planning: Besides as a diagnostic tool, Catastrophe Archetypes can function more proactively as a planning tool. They allow looking ahead and reveal how our doing may affect the system over time. They give scientists and managers the opportunity to examine and to test systems about their tendency towards catastrophic behavior. Potential problems can be detected and ways to achieve a desired outcome may be tested in advance. We assume that systemic causes for catastrophic behavior have to be anticipated for being able to find fundamental systemic solutions – which are radically different from mere symptom cures (Senge 1990, Ossimitz and Lapp 2006a) – for catastrophe hazards.

Theory Building: Based on Catastrophe Archetypes, it is possible to make general prognoses and give recommendations that are beyond the specifics of an individual case. Their generic structure can be used as a basic component of models that expose catastrophic tendencies. Catastrophe Archetypes allow conceptualizing archetypical forms of catastrophe management that may help to develop strategies appropriate to the concrete situation.

Identifying and Modeling of Catastrophe Archetypes

We identify the different Catastrophe Archetypes by combining two resources: (1) General systems research on archetypes (Senge 1990, 1994; Kim 2000a, 2000b, 2000c; Wolstenholme 2003, 2004; Marais et al. 2006) and (2) the exploration of systemic structure of concrete catastrophe scenarios in different fields as exemplary case studies. For modeling Catastrophe Archetypes we use both qualitative methods (e.g. causal loop diagrams) and quantitative simulation models, using the System Dynamics method. Causal loop diagrams allow the identification of systemic feedback loops. The System Dynamics models should help to investigate the dynamic behavior of Catastrophe Archetypes over time and give clues about conditions when catastrophes do or do not occur.

	(General) System Models	(Specific) Catastrophe Models
qualitative Approach	System Archetypes (Senge)	Catastrophe Archetypes
quantitative Approach	System Dynamics Molecules	SD models of Catastrophes

Figure 2: Qualitative and quantitative approaches to systems and catastrophes

Figure 2 shows that systems in general and catastrophes in particular can be modeled qualitatively or quantitatively. Hereby, System Dynamics Molecules are building blocks of commonly used model structures. The focus of our work is on the right hand side of Figure 2, covering both the qualitative and quantitative approaches. We will use the findings and results of general systems modeling (left column) as a starting point for our more specific investigations on modeling catastrophes (right column), using the System Dynamics method.

A Set of Catastrophe Archetypes

In our research on ISTC we are about to identify a set of different generic structures that (potentially) cause catastrophes, which we call Catastrophe Archetypes. As we are still in an early stage of theoretical work on ISTC, we have the following types of Catastrophe Archetypes as a working hypothesis. We plan to find out how these archetypes may be formalized qualitatively and quantitatively.

(1) *Attached catastrophe*: A stable system is suddenly subjected to a catastrophe. The long term behavior of the system is overruled by some short term catastrophe scenario. We call this type of catastrophe “attached”, because it can be modeled by attaching a catastrophe scenario to a calm “normal” system model. In Figure 3 the concept of the Attached Catastrophe Archetype is illustrated for an epidemic in a population. In an evenly developing population, an epidemic catastrophically interferes with the slow-pace-development of the population. Typically attached catastrophes are accelerated in comparison to the “normal” emergence of the system. When simulating attached catastrophes one has to combine a system-model representing the normal non-catastrophe system behavior with a catastrophe scenario. Usually the catastrophic scenario emerges over a much shorter time-span than the “normal” development. In the case of an epidemic in a population we have to model the development of the epidemic in steps of days or weeks, whereas for the “normal” development of the population a time-step of one year is common. It might happen that the catastrophic scenario requires the model to function according to a completely different set of rules, which represent the catastrophic behavior in contrast to the usual non-catastrophic behavior of the system. E.g. for modeling the flow of a river a flooding of the river will give the water new flow-paths and basins (for delaying downstream flows), which are not available for the normal water-flow in the bed of the river. When modeling attached catastrophes with System Dynamics we build the model in a way that the attached catastrophe scenario can be switched on in order to let a catastrophe overrule the normal development of the system.

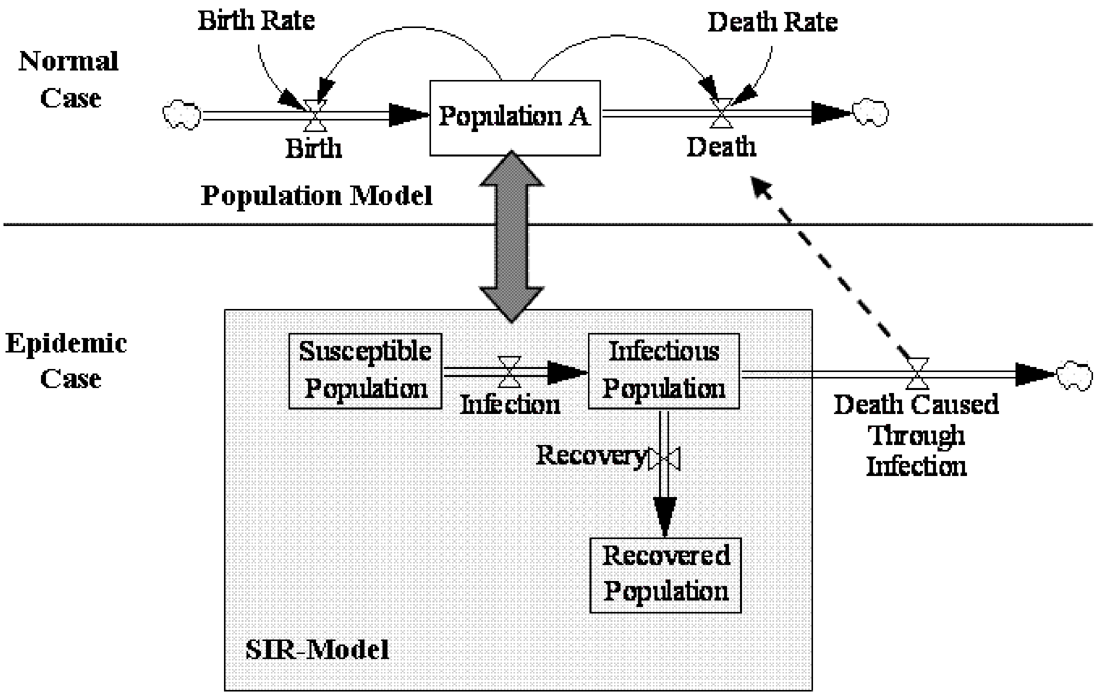

Figure 3: Concept of Attached Catastrophe Archetype

(2) ***Escalation catastrophe*****:** The possibility of a catastrophe is included within the system structure through an escalating feedback loop. We differentiate between two basic concepts of an escalating system. In Figure 4 concept 1 is shown.

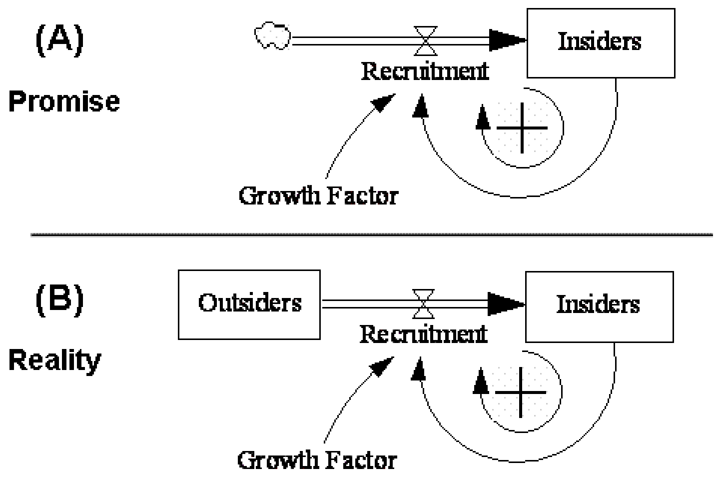

Figure 4: Concept 1 of Escalation Catastrophe Archetype (Ponzi-Scheme)

Here a system existentially needs growth for its survival and as consequences is prone to death in the long run. When growth stops, the system is doomed to collapse. For example a Ponzi scheme (a fraudulent investment scheme that pays high returns to existing investors just by the contributions of an exponentially growing number of new investors) can only carry on as long as new investors enter the business. If no more new investors can be found (which is inevitable due to the exponentially growing need of new investors), the Ponzi-scheme will break down sooner or later. We offer two variants of the process. In Variant (A) the focus is upon the exponential growth process, which appears to be infinitesimal. This represents the view of the proponents of the Ponzi-Scheme. The reality of any Ponzi-Scheme is displayed in variant (B). We can see that the pool of outsiders for recruitment is limited. It drains out through the recruitment process, until no one is left and the Ponzi-Scheme is doomed to death, since it can live only as long as there is a sufficient inflow of newly recruited insiders.

Another concept of an Escalation Catastrophe Archetype is illustrated in Figure 5. An example for Figure 5 is the arms race of the former superpowers USA and USSR (Senge 1990). More weapons on one side yield to more weapons on the other side and vice versa as one feels put at risk through the increasing armament of the other. Here the escalation is due to a mutual increase of two stocks. In the long run the escalation must stop due to a limiting factor or limiting cycle (not included into the model).

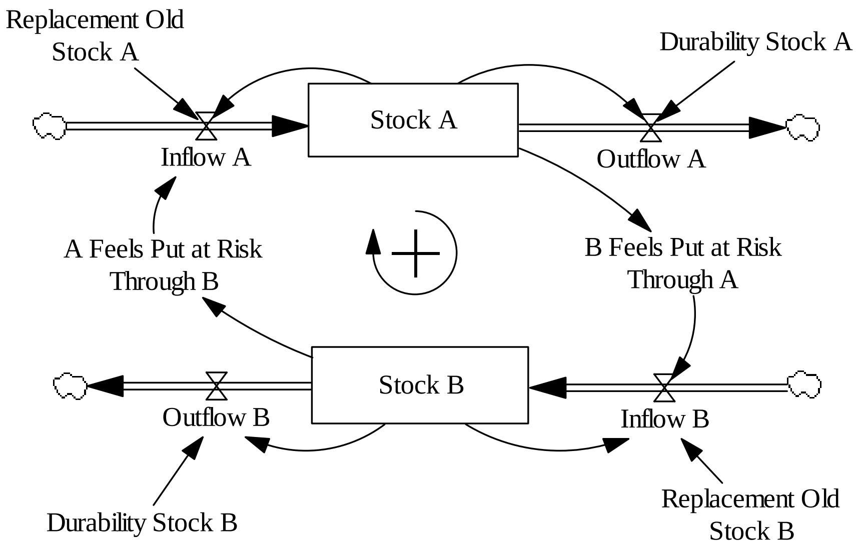

Figure 5: Concept 2 of Escalation Catastrophe Archetype

A tricky aspect of this Catastrophe Archetype is the fact that the escalation itself is not considered to be a catastrophe. The catastrophe lays either in the fact that the escalation process ceases at some time or in the side-effects the growth of both stocks have for the system. In the case of the military armament of USSR and USA the Soviet Union economically collapsed.

(3) *Overload catastrophe*: This Catastrophe Archetype describes how a self-regulating system can shift into a self-escalating system. For example, many people have to read and answer every day a not eligible amount of emails. To keep the system at equilibrium it is necessary to work-off existing emails in the same rate of incoming emails. However, if the work-off-rate decreases or the amount of incoming email rises the total amount of emails not worked on increases. At some point in time people are overstrained to read and answer all their mails. They can not handle any longer all the emails they should work-off. As a consequence frustration and unproductiveness may occur because of the huge stack of emails not worked on, often decreasing the work-off rate even more. Another example of an overload catastrophe are traffic-jams. A fundamental theoretical research question for this type of catastrophe is to identify efficient strategies to prevent overload catastrophes. Similar, Rudolph and Repenning (2002) develop a System Dynamics model that examines the role that non-novel events play in disasters.

(4) *Overshot and collapse*: In this Catastrophe Archetype a system grows beyond its carrying capacity. The resulting overcapacity destroys the recovery potential of the system. A classical example is the tragically over-crowding of the mule deer at the Kaibab Plateau in Arizona. Here, hunting the natural enemies of the mule deer led to an overpopulation of the deer due to enormous growth of the deer-population far above the carrying capacity of the plateau in the 1920th. In two successive winters many of the deer died of starvation (Ossimitz 1990). An important theoretical issue is the question how to foresee overshoot processes, since carrying capacities are not as evident as capacity limits of a bathtub or rain barrel.

(5) *Tragedy of Commons*: This system archetype (described by Senge, 1990) is also a Catastrophe Archetype. Individuals use a limited but renewable resource that is available to all persons free of charge as a common good. Since any of the persons is in fear that the others may narrow their own share everybody tries to exploit as much as possible from the resource. The final result is that the resource gets ultimately over-exhausted and the assets lessen for all individuals (e.g. overfishing).

(6) *Creeping catastrophe*: Systems referring to this Catastrophe Archetype show a long term time delay in their structure. Hence, the consequences appear slowly; they are typically irreversible. For example, the earth runs out of crude oil slowly but irreversibly. Another example is the gradual deforestation of the Easter Islands by the Polynesians. The deforestation took hundreds of years that lead to an increase in soil erosion as rain washed away unprotected soil. As a consequence population carrying capacity of the Easter Island decreased from between 6000 and 10000 people to about 2000 people in 1786 when the first Europeans arrived (Sterman 2000).

CONCLUSION AND OUTLOOK

The Integrated Systemic Theory of Catastrophes (ISTC) will bridge the gap between research on specific catastrophes and systems science. It will allow including aspects of general understanding of catastrophes in management and systems education. Moreover, ISTC will give clues for understanding and simulating processes with catastrophe potential. This also will allow investigations of how to design systems that are sustainable even under catastrophe hazards. The ISTC will offer an additional systemic perspective on catastrophes of different specific fields. It will allow catastrophe researchers to identify Catastrophe Archetypes as systemic patterns with catastrophic potential in their special field of interest. This also will widen the scope of measures against concrete catastrophe hazards.

Catastrophe Archetypes will extend and concretize the concept of system archetypes (Senge 1990) for an exploration of the catastrophic potentials of different types of systems. On the level of quantitative simulation the Catastrophe Archetypes will form basic patterns of modeling catastrophes. Catastrophe Archetypes will also help to generate generic catastrophe models, thus understanding better the systemic structure behind different types of catastrophes. These systemic structures will also offer insights of how a change of system structure can help to reduce or avoid catastrophe risks.

System Dynamics models with implemented “catastrophe modules” can help to understand the interrelation between “normal” and “catastrophic” systems structures and systems behavior over time. A crucial issue will be the question how and under which condition the model changes between the “normal” and “catastrophic” behavior.

Summarizing our expectations we propose that Catastrophe Archetypes will have consequences on the following different levels: for catastrophe research in specific fields, for modeling specific catastrophes systemically, for including catastrophe aspects into existing systems models, for management and systems education.

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