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MODELLING EXTREME EVENTS FOR THE PURPOSES OF SECURITY FORESIGHT

The risk management approach is used increasingly in modern security planning. In this approach, planners attempt to assess the likelihood of an event and the potential loss if the event occurs, and then to select certain measures that minimise an integral criteria of risk over some set of events. However, certain events of low probability but high potential impact, referred to as 'extreme' or 'catastrophic' events, need to be treated differently than those with a low potential loss and a high likelihood of occurring. This paper presents a brief overview of six 'methods' that have been used in addressing security-related risk management tasks—extreme value theory, catastrophe loss models, black swan theory, dynamic modelling, agent models, and complexity studies—and provides examples. It presents a summary on areas of implementation and underlines the limitations of established risk management approaches.

Keywords: *Extreme Value Theory, Catastrophe Loss Models, Black Swan theory, dynamic modelling, agent models, complexity studies, security policy, planning.*

Introduction

Risk management is a well established approach in engineering disciplines. Recent international standards recommend implementation of the approach by public, private or community enterprises, associations, groups or even at individual level [1]. The ISO 31000 standard is considered applicable to any type of risk, throughout the life of an organization, and to a wide range of activities, including strategy development, operations, processes, functions, projects, products, and services. The risk management approach is increasingly applied in support of decision making processes in the field of security [2]. Attempts have been made to apply it in a comprehensive framework, addressing all threats and hazards and thus to facilitate foresight-based decisions on investments in security [3], [4].

As a step in risk management, risk *assessment* includes identification of risks and evaluation of their potential impact. Quantitatively, risk assessment requires calculations of the likelihood that a certain event will occur and the magnitude of the potential loss if the event occurs. In security applications, however, there are events of very low probability but high negative impact, e.g. the earthquake in March 2011 near the coast of Japan, the consequent tsunami and the Fukushima nuclear disaster. Such events can be designated as 'extreme' or 'catastrophic.' Empirical data on such events is scarce. They are deeply uncertain and introduce high sensitivity of potential decisions to assessments of likelihood and impact. Hence, they cannot be treated in the same framework with events with a high likelihood of occurrence but a low potential loss.

This paper presents a brief overview of six 'methods' that have been used in modelling extreme events addressing security-related risk management tasks – extreme value theory, catastrophe loss models, black swan theory, dynamic modelling, agent models, and complexity studies. Each of the following sections describes a method and provides examples of its implementation.

The final section summarises the areas of implementation and points out again to the limitations of established risk management approaches.

Extreme Value Theory

Extreme Value Theory is a branch of statistics dealing with the extreme deviations from the median of probability distributions (fat tails, outliers). It is applied in the assessment of risk for highly unusual events – rare events with significant impact. The basic theory approach conforms to the first theorem in extreme value theory (Fisher and Tippett, 1928; Gnedenko, 1943). The Fisher–Tippett–Gnedenko theorem (also the Fisher–Tippett theorem or the extreme value theorem) is a general result in extreme value theory regarding asymptotic distribution of extreme order statistics. The maximum of a sample of independent and identically distributed random variables after proper renormalization converges in distribution to one of three possible extreme value distributions [5]:

- Type I or Gumbel distribution;
- Type II or Frechet distribution;
- Type III or Weibull distribution.

Available statistical data is pre-processed in two possible ways:

- Selecting data points only when the respective value surpasses a certain threshold (called *Peak Over Threshold*, or POT models);
- Taking the maxima for certain periods of time, e.g. annual or seasonal maxima for rainfall or intensity/ coverage of forest fires.

Expert opinion in which approach to choose and how to define thresholds is indispensable.

When adequate data is available, one can use general purpose software to find the appropriate probability distribution and its parameters. The method has been used to model large forest fires [6], extreme rainfall and earthquakes [7].

Catastrophe Loss (CAT) Models

CAT models are widely used by the insurance community and researchers supporting the formulation of insurance policies since the 1990s. Before that insurers and reinsurers would use the concept of the "probable maximum loss" (PML) in assessing risks. They employed recent historical scenarios for looking at "expected losses" and attempted to measure aggregate accumulations of loss in the zone(s) of interest. Since then, through 'Catastrophe Modelling' they replaced the PML with the exceedance probability (EP) curve. EP curves are a widely used output from a catastrophe loss model. An EP curve shows the probability of exceeding a monetary loss threshold. At the 1-in-100 year return period, there is a 99 % probability that losses will not exceed this level [8].

Resent studies have expanded the application of the method to include assessment of losses beyond the immediate impact of the extreme event. These assessments are dependent on adopted policies, and serve in turn to evaluate potential policy measures.

The main problem in using CAT models relates to the availability of historical data to construct and validate the models. With scarce data, there is also the danger that catastrophe models are 'overfitted' to describe relatively few recent events that have been observed, with the result that further events will give rise to surprises when they do not behave exactly like the previous ones. Another problem is uncertainty: "Failure to include the major sources of uncertainty in CAT models will lead to a systematic understatement of risk" [9]

The method has been used to model the impact of hurricanes, cyclones, extreme storms, earthquakes, landslides, volcano eruptions, corrosion in pipelines, outbreaks of infectious diseases, and terrorist acts.

Black Swan Theory

Black Swan theory concerns high-impact, hard-to-predict, and rare events beyond the realm of normal expectations. It is intended to explain the non-computability of the probability of the consequential rare events using scientific methods (owing to the very nature of small probabilities), as well as the psychological biases that make people individually and collectively blind to uncertainty and unaware of the massive role of the rare event in historical affairs. Nassim Taleb defines Black Swan as "an event with the following three attributes. First, it is an outlier, as it lies outside the realm of regular expectations, because nothing in the past can convincingly point to its possibility. Second, it carries an extreme impact. Third, in spite of its outlier status, human nature makes us concoct explanations for its occurrence after the fact, making it explainable and predictable." [10].

In foresight- /scenario-based planning such events are referred to as 'Unknown Unknowns' [11]. Taleb's understanding is not to attempt to predict Black Swan events, but to build robustness against negative ones that occur and be able to exploit positive ones. According to other authors, while one cannot expect perfect foresight, in fact past experience foreshadowed the possibility of the World Trade Centre and other disasters which points out the need for good methods of learning from past experience. March et al. discuss strategies for "learning from samples of one or fewer," which is often necessary in order to successfully avoid severe events. The general strategies they suggest include ways of viewing past history more "richly" (to extract as much information as possible from unique events), and using 'near misses' and hypothesized scenarios to enrich the available database [12].

The analysis of NASA's response to precursors to the Challenger disaster also shows the importance of being vigilant to incipient signs of problems, rather than ignoring or rationalizing them and minimizing the attendant dangers.

Methods of precursor analysis provide one strategy for using prior event information in estimating the frequencies of extreme events. Collection, reporting, and analysis of data on near misses or "precursors" to severe events are important steps to facilitate learning from past experience. Reporting of near misses is valuable for gaining qualitative insight into how (small) failures or errors develop into near misses or more serious events; arriving at a statistically reliable quantitative insight into the occurrence of factors or combinations of factors giving rise to incidents; and maintaining a certain level of alertness to danger and avoid complacency [13].

While perhaps less well recognized, analogies from prior events are also needed to estimate consequences, just as much as to estimate occurrence frequencies, since modelling or predicting the consequences of an event requires that we have some basis for predicting the particular conditions that are likely to occur afterwards.

Black swan theory has been used to explain space launch failure and pandemics. So far, its broader application to security foresight seems to be limited to appreciation of the need to consider 'unknown unknowns' in the conceptualisation of potential responses.

Dynamic Modelling

This group of methods and models uses historical time series data sets to characterize and reconstruct (often through predictive models) the dynamics of the emergence of extreme events. As input it uses empirical time series (historical records of intensity, location, timing, etc. of events of interest); consequences of extreme events within a given natural, social or ecological system, as well as on other systems with which it is coupled (e.g., environmental crises caused by human actions or socio-economic crises caused by natural effects). As output, it defines characteristics of the dynamics of emergence of extreme events and/or predictive models.

The following are along the main methods for characterization of the dynamics: spectral analysis; assessment of memory and long-range dependence, e.g. through the auto-correlation function; pattern recognition methods.

The dynamic models can be deterministic or stochastic, continuous or discrete in time, continuous or discrete in space. Boolean delay equations and kinetic logic, maps, flows, and automata are among the main groups of dynamic models used to explore extreme events [14].

Applications encompass modelling of natural events such as floods and extreme rainfall [15], earthquakes [14], and volcano eruptions [16].

Agent Models

Agent-based models (ABM) (designated also as *multi-agent systems* or *multi-agent simulations*) constitute a class of computational models for simulating the actions and interactions of autonomous agents—both individual and collective entities such as organizations or groups—in order to assess their effects on the system as a whole. The models simulate simultaneous operations and interactions of multiple agents, aimed at recreating and predicting the appearance of complex phenomena. A key notion is that simple behavioural rules generate complex behaviour at system level. Individual agents are typically characterized as boundedly rational, presumed to be acting in what they perceive as their own interests, using heuristics or simple decision-making rules.

Typically, agent-based models are composed of:

- numerous agents specified at various scales (typically referred to as agent-granularity);
- decision-making heuristics;
- learning rules or adaptive processes;
- an interaction topology;
- a non-agent environment.

From a systems analysis perspective, disastrous events are usually seen as resulting from complex interactions between different systems, such as physical, social, economic, etc. In participatory approaches to policy making, on the other hand, agent models allow to emphasise the involvement of various concerned interest groups and thus to evaluate policy options.

It is recognised that analytical solutions producing optimal allocations are impossible, due to the complexity of the policy problem, and the large amount of stochastic variables in particular. Hence, as input agent models use goal functions, constraints, distributions; spatially explicit data, e.g. water basins, urban and water management infrastructure, etc.; catastrophe generation; space of initial solutions and serve, for example, to assess policy decisions *vis a vis* a single overarching goal.

Agent-based models are used in simulations to adaptively improve the values of the policy variables according to the goal function, in combination with Monte-Carlo simulations.

Agent models have been used to model the impact of floods and to evaluate alternative policies for addressing the hazard and its consequences [17], [18]. Other security related applications aim at identifying conditions for emergent behaviour [19].

Complexity Studies

By 'complexity studies' we denote methods drawing from studies of complexity and self-organization. At the end of the 1980s it was discovered that a wide range of models and natural phenomena—landslides, wildfires, and earthquakes—exhibit 'self-organized criticality,' thus triggering interest in the application of respective methods in the study of extreme events [20].

The application of methods from complexity theory is based on observation of power laws in the frequency-size distributions of natural (and some social) phenomena. Such power laws indicate presence of fractal structures. It was suggested as a consequence that in addition to the three features of extreme events, listed above—rarity, irregular occurrence, taking extreme values—they have to be studied as inherent to the system under study, rather than being due to external shocks [21].

Self-organized criticality builds on the hypothesis that many complex phenomena can be explained by simplistic physical laws and/or one underlying process. The method studies the internal interactions in large systems. Specifically, it states that large interactive systems will self-organize into a critical state (one governed by a power law). Once in this state, small perturbations result in chain reactions, which can affect any number of elements within the system.

The respective models describe interactions of many elements according to fairly simple rules and attempt to replicate natural phenomena. Once the model is considered valid, it can be used to understand the conditions under which extreme events occur.

Since the 1990s a number of models have been developed to study natural phenomena emerging as a result of the internal dynamics of large systems. Among them are:

- the sandpile model used to study landslides and avalanches;
- the forest-fire model used in studies of wildfires;
- slider-block models implemented in earthquake research [22].

Summary of Implementation

Figure 1 outlines decision support issues addressed by modelling extreme events and the interfaces among them. The development of models can be based both of real world data and simulation results. Then, models are applied in addressing specific issues, as follows:

- Extreme value theory models are built on available empirical data and then used to model the respective hazard, utilising the probability distribution to estimate likelihood of occurrence and intensity. This in turn feeds into the scenario generation process.
- Dynamic models are used to characterise and understand better the dynamics of emergence of extreme events. They are built on empirical time series as well as simulation data and records on consequences of extreme events within a given natural, social or ecological system. Dynamic models are used primarily in scenario generation involving both the hazard and the object, or system, influenced by it.
- Black swan theory also provides insight on issues depicted in the upper left corner of Fig. 1. It is used to extract information from a very few empirical cases or 'near misses' and to expand the space of options considered in the scenario generation process.
- Methods drawing from studies of complexity and self-organization examine the hazard and the system under its influence in their mutual dependencies. They are built on historical records, e.g. interoccurrence and recurrence times of earthquakes, and the characteristics of the physical environment. Then they are used to calibrate models of natural phenomena.
- Agent models are built on the understanding of driving forces and rules of behaviour, and calibrated for compliance with empirical data. They represent the complex of a hazard, 'objects' under its influence and policies. Then agent models are used to estimate the impact of the hazard and assess capability requirements and policy options in preventing, reacting to, and managing the consequences, as well as on resilience enhancement.
- CAT models cover most fully the issues depicted on Fig. 1. They also treat jointly hazards and systems under its impact. Then, CAT models are used to estimate potential losses and to facilitate the development of insurance policies.

In view of recent catastrophic events, policy and expert communities are becoming increasingly aware of the limits of established risk analysis and risk management approaches [23]. Such hazards cannot be treated in the same framework as more regular events with a well understood impact. However, there is no unifying theory allowing to treat rigorously extreme events in support of the development of security policies. The examples here provide a glimpse on the growing field of theoretical studies on the modelling of extreme events and their practical implementation and thus contribute to a discourse of a huge practical significance.

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For more information visit the project website at http://www.focusproject.eu.

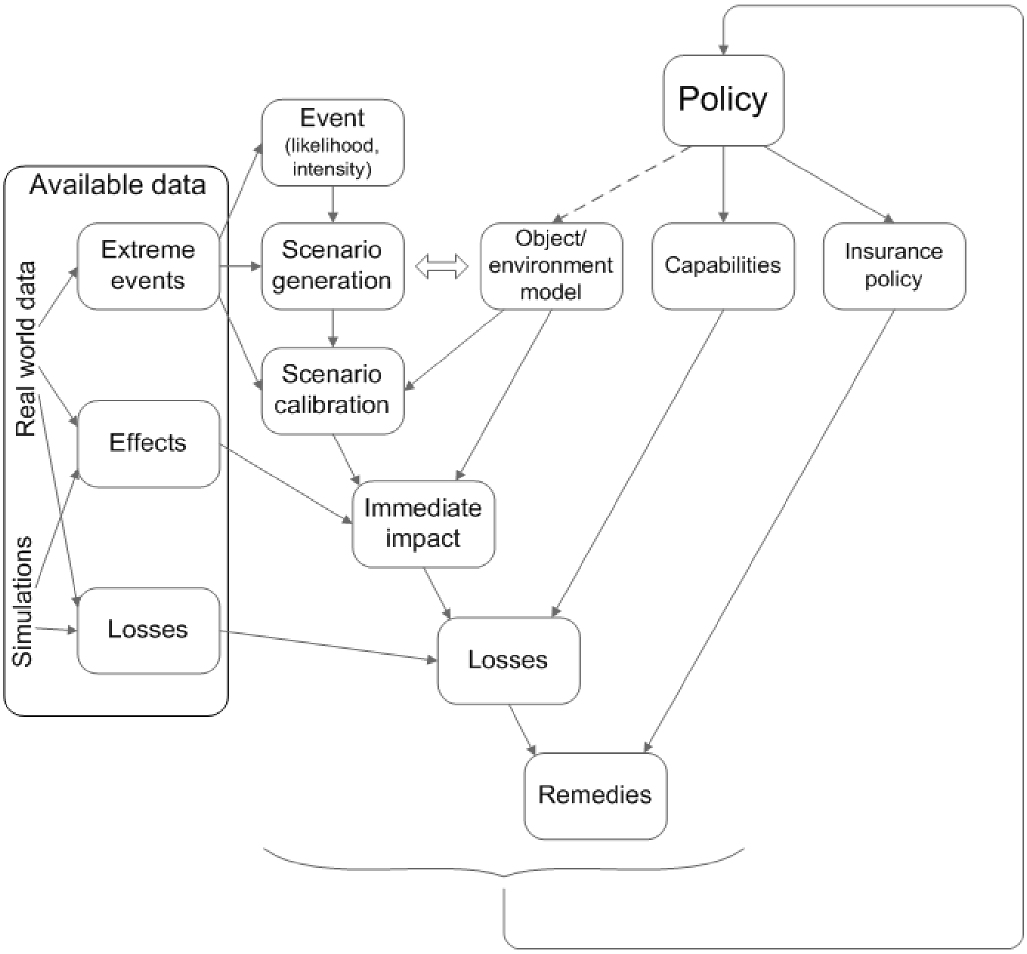

Fig. 1. Decision support issues and implementation of methods
for modelling extreme events

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МОДЕЛИРОВАНИЕ ЭКСТРЕМАЛЬНЫХ СОБЫТИЙ ДЛЯ ПРОГНОЗИРОВАНИЯ ИНФОРМАЦИОННОЙ БЕЗОПАСНОСТИ

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В современном планировании безопасности использование подхода к управлению рисками значительно увеличивается. В данном подходе, планировщики стремятся оценить вероятности событий и потенциальных потерь при наступлении событий, и затем выбрать определенные мероприятия для минимизации интегрального критерия риска для некоторого множества событий. Однако, события с малой вероятностью возникновения, но большим потенциальным фактором воздействия, относящиеся к т.н. «экстремальным», или «катастрофическим», должны рассматриваться по-другому, в отличие от тех событий с большой вероятностью возникновения, но малым фактором воздействия. Статья представляет краткий обзор шести «методов» с примерами, которые использовались для решения задач управления рисками, относящимися к информационной безопасности – теория экстремальных значений, модели катастрофических потерь, теория черного лебедя, динамическое моделирование, агентные модели, исследования сложности. Статья представляет собой основную информация по областям применения и подчеркивает ограничения установленных методов управления рисками.

Ключевые слова: теория экстремальных величин, модель ущерба от техногенных аварий и катастроф, теория черного лебедя, динамическое моделирование, агентные модели, исследование сложности, политика безопасности, планирование.

МОДЕЛЮВАННЯ ЕКСТРИМАЛЬНИХ ПОДІЙ ДЛЯ ПРОГНОЗУВАННЯ ІНФОРМАЦІЙНОЇ БЕЗПЕКИ

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У сучасному плануванні безпеки використання підходу до управління ризиками значно збільшується. У даному підході, планувальники прагнуть оцінити вірогідності подій та потенційних витрат за настання подій, і потім вибрати певні заходи для мінімізації інтегрального критерію ризику для деякої множини подій. Однак, події з малою вірогідністю появи, але великим потенціальним фактором впливу, що відносяться до т. з. «екстремальних», або «катастрофічних», повинні розглядатися по-іншому, на відміну від тих подій з великою вірогідністю появи, але малим фактором впливу. У статті викладено короткий огляд шести «методів» з прикладами, які використовувались для рішення задач управління ризиками, що відносяться до інформаційної безпеки – теорія екстремальних значень, моделі катастрофічних витрат, теорія чорного лебедя, динамічне моделювання, агентні моделі, дослідження складності. Стаття становить собою основну інформацію по областям застосування і підкреслює обмежень встановлених методів управління ризиками.

Ключові слова: теорія екстремальних значень, модель збитку від техногенних аварій та катастроф, теорія чорного лебедя, динамічне моделювання, агентні моделі, дослідження складності, політика безпеки, планування.

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