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Modelling Project Problem Spaces with General Morphological Analysis

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Abstract: The European Union sponsors numerous consortium-based, multinational, transdisciplinary projects which deal with complex socio-technical systems and planning processes. General Morphological Analysis (GMA) is a non-quantified modelling method which has been employed in a number of such projects to carry out four important tasks: (1) to collectively develop – as early as possible in the project process – a conceptual model of the overall Project Problem Space (PPS); (2) to use subsets of this general PPS framework for modelling more specific structures and processes needed during the project; (3) creating illustrative graphical models and methodological tools for the final project delivery, and which can later be used by end-users, and (4) using the evolution of the PPS as an "audit trail" for post-project evaluation and lessons learned. The initial (early) collective development of the PPS is especially important for creating a common conceptual modelling framework and terminology to help get the diverse participating organisations and subject-specialists "on the same page" as quickly as possible. This article presents examples of how these four modelling roles have been employed in the EU 7th Framework Program project "FORTRESS", carried out from 2014-2017.

Keywords: general morphological analysis, project problem space, non-quantified modelling, conceptual modelling, Gap-analysis, modelling assessment, applicability of modelling methods.

1. Introduction

Over the years, the European Union has sponsored numerous consortium-based, multinational, transdisciplinary[*] projects concerned with complex societal problems involving (1) interactions between technical, political, organisational and legal systems; (2) cross-border and cross-cultural co-operation between diverse types of organisations and institutions (e.g. government authorities, academic research institutions, private companies and NGOs); and (3) multi-stakeholder policy positions.

Proposing and carrying out such projects presents us with a number of difficult methodological issues. One of them is an *epistemological* problem concerning the applicability of different modelling methods to different modelling tasks. Another is a *project managerial* problem concerning getting the diverse participating organisations and subject-specialists "on the same page" and working effectively together as quickly as possible.

[*] Transdisciplinary Research is defined as research efforts conducted by investigators from different disciplines working jointly to create new conceptual, theoretical, methodological innovations that integrate and move beyond discipline-specific approaches to address a common problem. [Harvard Transdisciplinary Research in Energetics, https://www.hsph.harvard.edu/trec/about-us/definitions/]

I. ***Epistemological*** **(modelling)** ***issues***.

One of the major methodological problems encountered in projects involving a complex mix of technical-social-political, legal and even ethical issues, is the question of the applicability of different modelling methods to different modelling targets and tasks. Firstly, many of the variables involved are not meaningfully quantifiable, as they contain strong social, political and cognitive dimensions. Secondly, the uncertainties inherent in such problem complexes often cannot be (significantly) reduced or even adequately described. This includes so-called *agonistic uncertainty* i.e. conscious, self-reflective and potentially conflicting actions among numerous actors/stakeholders. Finally, interactions between large networks of social-technical-organisational systems are extremely non-linear, with parametric relations between variables continually shifting in unpredictable ways. This is the very definition of what has been termed *wicked problems*.

Such problems have no analytical modelling solutions and no stable, well-grounded probability distributions. This means that traditional deterministic (e.g. system dynamics), probabilistic (e.g. Bayesian) methods and/or computational simulation will not suffice. One also needs recourse to dynamic modelling methods that can deal with non-quantified variables, with *modal categories* (possibility/impossibility, plausibility), and with *normative* constraints involving goals, values, motivations and other "subjective" forces.

II. ***Project management and work-flow***

Another problem with multinational/transdisciplinary projects is that of getting the diverse organisations and subject-specialists "on the same page" as quickly as possible. One might think that the relatively long and comprehensive task of collectively developing a consortium *project proposal* would itself serve to bring the diverse consortium members involved to an adequate collective understanding of the project's overall objectives, and provide sufficient insight into each other's respective roles, tasks and areas of responsibility. However, in my experience this is almost never the case. It often requires several months, sometimes far longer, to get the diverse national and discipline-based organisations to fully understand their own, and others', roles and obligations, and thereby meshed into a well integrated working framework. (In my experience, *discipline-based differences* and *organisational culture* are more of a problem than *national*-cultural or language differences.) In the worst cases, this integration never fully comes about throughout the entire project.

In this article, I wish to demonstrate how an early collective conceptual modelling of the Project Problem Space (PPS), using the non-quantified modelling method General Morphological analysis (GMA), can help to alleviate both of these problems. In addition, in Section 4, a GMA-based Modelling Assessment Framework is presented that can be used to make an inventory of the project's modelling requirements and test the applicability of different modelling methods to different modelling tasks and targets. An early discussion of this issue is definitely needed in projects dealing with multi-stakeholder, policy driven societal problems.

2. GMA's four roles in conceptual project modelling

The four main modelling roles that GMA can play in projects are:

1. **At the beginning of a project** (e.g. as an extension of the "kick-off" meeting): to bring together relevant competencies in the project consortium in order to *collectively* model the total Project Problem Space (PPS) and to map out the relevant interconnections between the different parameters of this space. This master PPS serves to carefully define the problem complex, to "bound the problem", to create a dialogue between different subject-specialists and stakeholders (e.g., CM-practitioners, academics, decision support specialists), and to give the participating organisations a *common terminology* and *common conceptual framework*.

   Also – *and this should not be underestimated* – the PPS process gives the needed opportunity for different consortium members, different disciplines and different personalities to confront one another, define their respective "territories", roles and the general "social structure" of the working group. This process has to take place sometime and somehow – whether we like it or not. So it is definitely better that it is done under controlled circumstances, in order to get though it as quickly and painlessly as possible. Collectively modelling the PPS with the aid of an appropriate modelling method and a professional facilitator is the ideal circumstance for this initial "socialisation" process.

2. **During the project:** to use sub-sets of parameters abstracted from the (master) PPS in order to treat more specific *non-quantified modelling problems*. This includes scenario and strategy models, organisational structure/change models, stakeholder/position models, Gap-analyses, assessment tools, etc. Some of these can be *anticipated* and programmed into the initial project proposal. Others, however, can emerge as "needs" during the course of the project. Also, especially during longer (e.g. 3+ year projects) it is often the case that one or more of the *work-packages* (WPs) may need their own "initial conceptual modelling" phase, as in point 1, above.

3. **For the project report and dissemination phase:** to create a number of non-quantified inference models that can demonstrate the *results* of the project, but which cannot be (meaningfully) rendered as quantitative (deterministic or stochastic) models. These morphological models can also be delivered as computer-based tools, where the recipients of the project's results receive software in order to run them. Such *demonstrators* and *tools* have shown themselves to be greatly appreciated by stakeholders, domain experts and potential end-users.

4. **As a project evaluation framework**: The PPS can also serve as an "audit trail" and a post-project evaluation tool. All R&D programs/projects must be able to allow for the identification and development of new concepts, knowledge and "problem dimensions" during the course of the project. The initial PPS must be able to evolve and record such "discoveries" as they emerge.

3. Case-Study FORTRESS

To exemplify how these four modelling roles can be applied, I have chosen a project from the 7th Framework Programme: "FORTRESS: Foresight Tools for Responding to Cascading Effects in a Crisis" (April 2014 to March 2017). The general aim of project FORTRESS was to produce methods and tools in order to better understand cascading effects of infrastructure disruptions in crisis situations, and to improve future national and cross-border planning, preparedness and response.

> FORTRESS will identify and understand cascading effects by using evidence-based information from a range of previous crisis situations, as well as an in-depth analysis of systems and their mutual interconnectivity and (inter-)dependency. FORTRESS will seek to intervene in current crisis response practices by bridging the gap between the over-reliance on unstructured information collection on one side and a lack of attention to structural, communication and management elements of cross-border and cascading crisis situations on the other. It will use state of the art information collection and modelling tools to assist stakeholders in evaluating what information is significant, relevant and of greater priority so that they can adjust their actions accordingly. [*] [From the Project Description]

During project's three-year time span, four morphological modelling tasks were carried out in support of four different work-packages. Two of these tasks (1 & 4 below) were built into the original project proposal; the remaining two (2 & 3) were developed after the need for them was discovered during the course of the project.

1. The collective development of a PPS which served as a *common conceptual modelling framework* for the project participants and also as an "audit trail" and a post-project evaluation model. This was done in connection with the first "kick-off" meeting and was built into the original project proposal.

2. Employment of a sub-set of variables from the PPS framework in order to structure and inter-relate a number of *historic case studies* and *scenarios* of cascading effects of infrastructure disruptions. The idea of employing GMA in this context, and the advantages it brought with it, was discovered during the initial development of the PPS.

3. The development of a modelling framework for *cross-border issues* to enhance cooperation and planning. The possibility of this model was discovered as a result of the output of #2 (above).

4. The development of a *gap-analysis* model to identify discrepancies between "pathogenic factors" (infrastructure/institutional vulnerabilities) and factors of resilience and vulnerability reduction. Since GMA's basic structure is known to be well-suited to gap-analysis, this was programmed into the initial project proposal.

[*] For a detailed description of the project & results, see: https://cordis.europa.eu/project/rcn/185488/factsheet/en

3.1 Model #1: Modelling the initial "Project Problem Space" (PPS)

The PPS modelling process was based on the following (initial) *Focus Question*:

> What are the most important/relevant parameters (i.e. factors or variables) concerning *cascading effects of disruptive events on critical infrastructure*, and how do these parameters relate to one another?

Twenty parameters were identified for the initial PPS:

1. Possible types of *natural* hazards
2. Possible types of *technological* hazards
3. Possible types of (non-antagonistic) *social* hazards
4. Possible types of *antagonistic* hazards
5. Geographical level/scope of disruption
6. Cross-border status
7. Location of primary disruption
8. Time scale of event
9. Mode of Impact
10. Sector capacities directly/primarily affected
11. Sector capacities affected as a secondary effect of primary impacts
12. Criticality of infrastructure/capacity components
13. Type of interdependency
14. Responsible authorities
15. Coordination level
16. Warning/Prediction mechanisms
17. Disaster cycle
18. Type of disaster response information available
19. Resilience factors
20. Types of Networks involved

Each of these parameters was then broken down into a domain of relevant *values* or *states*. The sum total of the parameters and their domains defines what is called a *morphological field* or *morphospace*. This is the first conceptual framework for the project as a whole (Figure 1).

Note that the scope of this (initially unbounded) problem space may be larger than the *actual* Project Problem Space that would eventually be employed in the project. However, in the initial iteration of the problem structuring process, it is preferable to start with a *maximal space*, which can then be systematically bounded, rather than initially assuming boundary conditions at the risk of missing significant factors or conditions. The bounding process can take place once the maximal problem field is scrutinised by all of the project partners.

The choice of these *parameters* was brainstormed by the working group, in order to represent the main variables within the problem space. The parameters' respective *domains*, however, were taken (when possible) from the international Crisis Management (CM) literature, in order to be more readily recognisable for different stakeholders. The initial *domains* are preliminary and can be adjusted or further developed during the course of the project.

1. Types of hazards (Natural)	2. Types of hazards (Technical)	3. Types of hazards (Social)	4. Types of hazards (deliberate antagon-istic actions)	5. Geo-graphical level/scope of impact	6. Cross-border status	7. Location	8. Time scale of event/ onset of crisis	9. Impact	10. Sector capacities directly/ primarily affected	11. Sector capacities affected because of primary effects	12. Criticality of components	13. Type of inter-dependency	14. Responsible authorities	15. Coordin-ation levels	16. Warning/ Prediction mechan-isms	17. Disaster cycle	18. Type of disaster response information available	19. Resilience factors	20. Networks involved
Floods	Radiation releases	Mass gatherings	Conven- tional terror attacks	Global	Multiple cross-border	Coast	Sudden (Seconds or minutes)	Single	Transportation GROUND	Transportation GROUND	Major node	Geographic	Police	EU	Prediction/ Forecasting	Mitigation	General sense-making information	Civil protection	Legal
Wildfires	Industrial accidents	Riots	CBRN attacks	International	Single cross-border	Plain	Rapid (Hours/days)	Recurrent	Transportation AIR-WATER	Transportation AIR-WATER	Will create cascade	Physical	Fire	National	Monitoring	Preparation	Geographical info	Crowd sourcing	Financial
Storms/ Snow storms	Transport accidents	Strikes	Cyber terrorism	National	Not cross-border	Hills	Slow (Weeks)	Cyclical	Energy production	Energy production	Used for rescue services	Cyber	Health	Regional	Technical/ administrative warning	Emergency response	Location	NGOs	Logistical
Landslides	Chronic pollution	Rumours	Hostage taking	Regional		Mountain	Creeping (months/years)	Cascading	Energy transmission and distribution	Energy transmission and distribution	Evacuation route	Logical/ functional	Local admin. Municipal govt.	Local	Evacuation	Recovery	Cause of situation	Business continuity	Social
Avalanches	Plant failure	Distrust in government	Insider threats	Local		Rural		Coincident	Water provision	Water provision	Supply route	Social/ communication based	Companies/ industry	Online	No warning	Reconstruction	Recovery time		Administrative
Earthquakes	Urban fires	Polarisation				Urban			Public communication (telecom)	Public communication (telecom)			National security				Who is responsible		
Tsunamis	Building collapse					Metropolitan			Waste & biochem	Waste & biochem			Insurance companies				Who needs info.		
Volcanoes	Dam failure								Healthcare (hospitals&clini cs)	Healthcare (hospitals&clini cs)			Civil protection authorities						
Extreme tempera- tures	Blackouts								Emergency services and national security	Emergency services and national security			MACC, CMC, etc.						
Drought									Economic services	Economic services			Civil society organisation						
Ice storms									Government sector (Decision & continuity)	Government sector (Decision & continuity)			Community based organisations						
Epidemics etc.									Social sector(Educati on, aggregation, ic	Social sector(Educati on, aggregation, ic			Intergovernme ntal organisations						
Space hazards									Residential housing sector	Residential housing sector									
									Environmental	Environmental									

Figure 1: Initial Project Problem Space (PPS) for FORTRESS. (Enlarged diagram in **Appendix 2**)

3.2 Model #2: Modelling Framework for Case Study Scenarios

One of the Work Packages was tasked to deliver as series of *case studies* in which a number of *historical disasters* were described in order to illustrate cascading or cross-border effects, including mapping networks of systems and actors. Instead of only developing scenario texts, it was decided to develop a common morphospace framework within which all of the case study scenarios could be "plugged into", making it possible to systematically compare them. For this purpose, a subset of the parameters in the PPS was extracted, together with additional *ad hoc* parameters in order to profile, describe and compare the case studies, and later, the scenarios to be developed from them.

The case study modelling framework was developed in a 2-day workshop with members of the involved *work package*. The parameters chosen for the model were:

1. Types of hazard
2. Principal nature of impact
3. Scope of impact
4. Onset of crisis
5. Scope of Crisis Management (CM) activities
6. Principal involved actors in CM
7. Directly affected sectors
8. Indirectly affected sectors
9. Triggers/principal causes for cascade

Nine *case studies* were subsequently profiled by this model (see the "Case" parameter in the morphological model shown in Figures 2 & 3).

Case	Types of hazard	Principal nature(s) of impact	Scope of impact	Onset of crisis	Scope of CM	Principal involved actors in CM	Directly affected sectors	Indirectly affected sectors	Triggers/ causes for cascade
Tsunami-Fukushima, Japan, 2011	Natural	Physical	Global	Sudden	Global	Police	Transportation GROUND	Transportation GROUND	Information
Firework factory explosion (2000) - Netherlands	Social	Social / Psychological	International & cross border	Rapid (Hours/days)	International & cross border	Fire	Transportation AIR-WATER	Transportation AIR-WATER	Communications
London attacks (2005)	Technological	Economic	National	Slow (Weeks)	National	Health	Energy production	Energy production	Physical Resources
Heat wave 2003 (Austria)	Antagonistic	Political	Regional	Creeping (months/years)	Regional	Local admin. Municipal govt.	Energy transmission and distribution	Energy transmission and distribution	Man-power
MH17 (2014)			Local		Local	Companies/ industry	Water provision	Water provision	Operational
Avalanche Disaster of Galtür, AT (1999)						National security	Public communication (telecom)	Public communication	Physical (infrastructure dependence)
Central European floods (focus on Prague) (2002)						Insurance companies	Waste & biochem	Waste & biochem	Cyber
Hurricane Sandy, USA (2012)						Civil protection authorities	Healthcare (hospitals&clinics)	Healthcare (hospitals&clinics)	Geographic / meterological
Eruption of Eyjafjallajokull in Iceland (2010)						MACC, CMC, etc.	Emergency services and national security	Emergency services and national security	Geological
						Civil society organisation	Economic services	Economic services	Functional/ logical/ policy related
						Community based organisations	Government sector (Decision & continuity)	Government sector (Decision & continuity)	
						Intergovernmental organisations	Social sector(Education, aggregation, icon)	Social sector(Education, aggregation, icon)	
							Residential housing sector	Residential housing sector	
							Environmental	Environmental	

Figure 2: Case study profile for Firework factory explosion in the Netherlands (2000).

Case	Types of hazard	Principal nature(s) of impact	Scope of impact	Onset of crisis	Scope of CM	Principal involved actors in CM	Directly affected sectors	Indirectly affected sectors	Triggers/ causes for cascade
Tsunami-Fukushima, Japan, 2011	Natural	Physical	Global	Sudden	Global	Police	Transportation GROUND	Transportation GROUND	Information
Firework factory explosion (2000) - Netherlands	Social	Social / Psychological	International & cross border	Rapid (Hours/days)	International & cross border	Fire	Transportation AIR-WATER	Transportation AIR-WATER	Communications
London attacks (2005)	Technological	Economic	National	Slow (Weeks)	National	Health	Energy production	Energy production	Physical Resources
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MH17 (2014)			Local		Local	Companies/ industry	Water provision	Water provision	Operational
Avalanche Disaster of Galtür, AT (1999)						National security	Public communication (telecom)	Public communication	Physical (infrastructure dependence)
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Hurricane Sandy, USA (2012)						Civil protection authorities	Healthcare (hospitals&clinics)	Healthcare (hospitals&clinics)	Geographic / meterological
Eruption of Eyjafjallajokull in Iceland (2010)						MACC, CMC, etc.	Emergency services and national security	Emergency services and national security	Geological
						Civil society organisation	Economic services	Economic services	Functional/ logical/ policy related
						Community based organisations	Government sector (Decision & continuity)	Government sector (Decision & continuity)	
						Intergovernmental organisations	Social sector(Education, aggregation, icon)	Social sector(Education, aggregation, icon)	
							Residential housing sector	Residential housing sector	
							Environmental	Environmental	

Figure 3: Comparison of "Firework factory explosion" (FFE) and "Avalanche Disaster of Galtür" (ADG). Light blue is only FFE; middle blue is only ADG; dark blue is "common ground".

Figure 2 shows the "Fireworks factory explosion" (FFE) in the Netherlands (2000), an industrial accident with high physical impact and cross-border effects.

When all of the case studies were added to the model, they could easily be scrutinised and compared – as in Figure 3. This is a comparison between the two case studies "Fireworks factory explosion" (FFE) and the Avalanche Disaster of Galtür (ADG) in 1999. Here we see the light blue cells representing FFE only; the middle blue cells representing ADG only; and the dark blue cells representing what was common to both.

3.3 Model #3: Modelling framework for cross boarder issues

One of the central concerns of the project was cross-border crisis situations and cross-border Crisis Management (CM) capabilities. This is a complex problem in itself which needs to be structured and given a modelling framework. Thus the second application was to focus on identifying and comparing different cross-border parameters (e.g. impacts, areas of cooperation, planning activities, legal structures, etc.), and also to relate these issues to different types of hazards and infrastructure vulnerabilities, and, eventually, to different types of national CM systems. Figure 4 shows the prototype Cross-border morphospace.

Areas of cross-border impacts of disaster	Areas of cross-border cooperation	Types of cross-border activities/ agreements	Extent of cross-border planning	Types of cross-border assistance and cooperation during disaster	Scope of cross-border cooperation
Transport	Financial (e.g. budget sharing)	Planning meetings	Full blue-light preparedness planning	share info	International/intergovernmental intervention (NATO, OCHA involved)
Energy	Administrative	Transnational boards	Response plan for specific case	share command	Supranational intervention (EU involved)
Health care	Legal	Written agreements	Standard routines for specific cases	share systems	International cooperation (Involving Nation States, typically bilateral dialogue or +)
Communications	Operational/ logistic	Service contracts	Only common alert plan	share plans	Inter agency cooperation (e.g. between two civil protection, not involving higher ranks of national governments). Small scale.
Water provision	Information (Information systems)	Shared procedure manuals	No common planning	share staff	Cross border cooperation (Not Existing protocols/practices/legal frame).
Waste & biochem		Cross-border training and exercises		share equipment	Cross border cooperation (Existing protocols/practices/legal frame).
Emergency services and national security		Development of inter-operability		share medical resources	State of crisis declared and request of emergency aid to international community (Y/N).
Economic services		Only informal interaction		Traffic rerouting	
Social sector(Education, aggregation, icon)		None		evacuations	
Government sector (Decision & continuity)					
Residential housing sector					
Environmental					

Figure 4: Prototype modelling framework for cross-border issues.

3.4 Model #4: Gap-analysis

A *Gap-analysis* is a method used to assess the difference (or "gap") between two states of an organization, an activity or a knowledge base. Most commonly, it is used to compare a *current state* of something with a *desired* or *potential future state*. The "gap" is the disparity of between what is and what is desired or ought to be. Gap-analysis can be applied to *performance*, *knowledge*, *skills*, *market strength* or any other measurable and comparable aspect of organisational life. It is used in order to better understand the requirements for change or development within the context of some organisational goal. A morphological model is highly suitable for gap-analysis, since it essentially shows all of the possible configurations (or possible states) of a system or process, so that these "states" can be compared.

One of the tasks of the project was to examine concepts of vulnerability and resilience in order to provide the basis for the development of an Incident Evolution Tool, which in turn could serve as a planning and decision support instrument. In support of this, a morphological gap-analysis model was developed in order to show the differences between an actual state of affairs as concerns *vulnerabilities* for a particular disaster *case study*, and what would be required in order to reduce these vulnerabilities and improve resilience. Thus the gap-analysis model consisted of two groups of parameters.

- *Vulnerability factors*: types of vulnerabilities, interdependencies and effects that describe a particular disaster
- *Resilience and vulnerability reduction factors*: variables that represent capacities, flexibilities and other systemic properties which can reduce vulnerabilities and/or improve preparedness, mitigation and crisis management.

The formal scheme for this Vulnerability-Resilience (V-R) Gap analysis is shown in Figure 5.

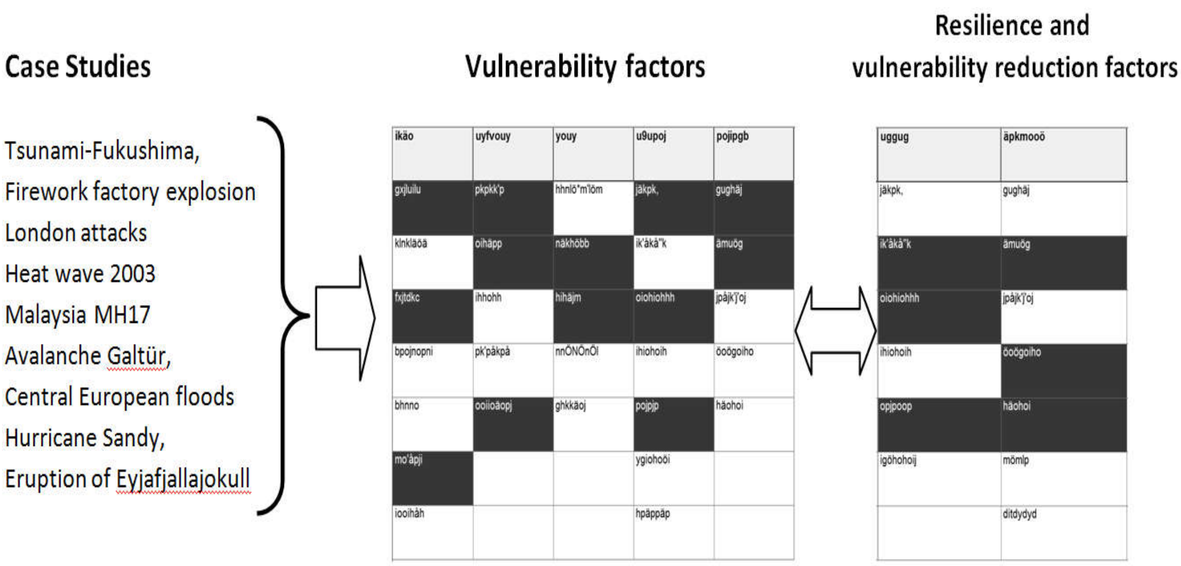

Figure 5: Schematic for V-R GAP analysis model.

The Gap-analysis example below (Figure 6) concerns the Earthquake of 2011 and the ensuing tsunami and Fukushima Nuclear Power Plant Disaster in Japan

The first six parameters of the model are *event descriptive inputs* based on the Fukushima case study. The **DARK BLUE** inputs express the main or primary conditions of the disaster, the **LIGHT BLUE** the secondary conditions.

Parameter #7 represents primary and secondary *vulnerability factors* associated with this case study.

For parameters 8 and 9 the **DARK BLUE** cells show those resilience and vulnerability reduction conditions that were already present at the outset of the disaster. The **RED** cells represent those appropriate conditions or actions that would have been needed in order to *improve* conditions concerned with preparedness, mitigation and crisis management of the disaster.

Vulnerability TYPE	Vulnerability assessment process	Inter-dependencies	Amplification	Areas Affected	Community Impacts	Vulnerability factors	Aspects of resilience:	Vulnerability reduction conditions/ actions
Economic	Geophysical Risk	Physical	Critical	Death and Injury	Individuals: direct	Production pressures(take over safety)	Capacity for successful response to chronic risk or sudden onset of disaster. (Risk dimension)	Homeostasis
Technological or technocratic	Engineering and Architectural Risk	Geographic	Containable	Physical Health /Well-being	Individuals: indirect	Failure of the regulatory/control authorities.	Capacity for overall functioning of people, communities, organisations or constituencies post-disaster.	Omnivory
Residual	Technological Risk	Logical	No amplification.	Mental Health/Wellbeing	Small groups: direct	Weakness of the organisational safety culture.	Capacity to deal with surprise in cascading events.	High flux
Delinquent	Medical Consequences	Cyber		Home/Shelter	Small groups: indirect	Limits of operational feedback.	Capacity for understanding the scope and magnitude of disaster effects in order to cope (Salutogenesis & Sense of Coherence)	Flatness
Newly generated	Socio -Economic Consequences			Safety and Civil Security	Community: direct	Flawed management of organizational complexity	Capacity for psychological resilience and integration of SoC scales in the routines of emergency managers and security professionals.	Buffering
Natural hazard related	Plan Organizational Response			Food	Community: indirect.	No consideration about a whistle-blower	Flexibility of international diplomacy.	Redundancy
Total vulnerability				Potable Water		Wrong design of mitigation measures/ models.	Capacity to mobilize effectively many resources with short time notice.	Some of above in place, but need improvement.
				Sewerage and public health systems		Social dependency on most interconnected sectors	Capacity to addresss latent vulnerabilities and limit the spread of cascading.	None of the above effectively present
				Information about services and support		Geographic concentration of Critical Infrastructures	Existence of an effective legal/political/admistrative framework	
				Access to services and support		Structural Weakness of Critical Infrastructures.	Some of above in place, but can be improved.	
				Income security/economic opportunity		Unsustainable development	None of the above effectively present	
				Social links, social networks and social support				
				Community owned assets				
				Community owned /shared intangibles				
				Transportation				

Figure 6: Vulnerability-Resilience (V-R) Gap for the Fukushima disaster

For a more detailed presentation of how GMA can be employed for gap-analyses, see Ritchey (2013).

4. Modelling Assessment Framework

As stated in the introduction, modelling complex social, technical and organisational systems presents us with a number of difficult methodological problems. The abundance of non-quantified variables, non-reducible (genuine) uncertainties and extreme non-linearity combine to make traditional mathematical and stochastic modelling problematic.

Of central interest here is the issue of modelling the interdependencies between different societal functions, systems and organisations. With what is essentially a complex *n-body problem*, employing mathematical (functional) modelling and/or computational simulation, in an attempt to predict how things are actually going to "evolve" concerning such interdependencies, is simply out of the question (at least with present-day modelling techniques). Even if we choose to disregard the social, organisational and behavioural aspects of these interactions, and only concentrate on "objective" variables concerning e.g. physical/informational connectivity and geographical proximity, there remains intractable modelling theoretical hinders to casually modelling or simulating the actual course of events.

This does not mean that we cannot produce useful models in order to help us better understand and deal with this problem. Here the emphasis is not on prediction as such, but on flexible operational planning, awareness building, training and instruction, and possibly a contribution to real-time decision support – as an "aid to judgement".

In this context, there are a number of different modelling techniques for mapping interdependencies in complex social-technical systems. These include:

1. Non-quantified influence diagrams (NIDs)
2. Quantified (Weighted), influence diagrams (WIDs)
3. General Morphological Analysis (GMA)
4. Bayesian Network Models (BN)
5. Systems Dynamic Modelling (SDM)
6. Agent Based Modelling (ABM)

Each of these methods has its advantages and disadvantages. However, it is not a case of advocating the exclusive use of one or another of the methods: we need to employ *all the methods we can muster* in order to illuminate the problem at hand. Furthermore, these methods represent a natural modelling progression, where the "simpler" methods (at the top) are broader and more flexible, and are necessary prerequisites for the more "complex" ones.

The choice of modelling method(s) depends on the nature of the modelling task, including the nature of the "object" (target) to be modelled, the type of empirical information available concerning this "object", and the nature of the uncertainties involved. Here we present a prototype meta-modelling framework, developed as a *dialogue instrument,* in order to scrutinise how different modelling methods can be used for different modelling tasks and targets.

The meta-modelling framework contains the following parameters.

1. What is being modelled
2. Purpose or goal of the modelling
3. Main intended final result
4. From where is the principal knowledge derived
5. Main type(s) of information that are available
6. Chief method of approach
7. Modelling mode
8. Type(s) of competence required
9. Type(s) of uncertainty involved
10. Uncertainty transformation
11. Method of validation (where possible)
12. Specific modelling methods that can be employed

Figure 7 shows the 12-parameter prototype Modelling Assessment Framework. Figure 8 is an example of a modelling profile for modelling case-studies of infrastructure disruptions and cascading events. This prototype can be refined and adapted for the specific requirements and conditions of a particular project.

What is being modelled	Purpose or goal of modelling	Main intended result of the model	From where is principal knowledge derived	Main type(s) of information available	Chief method of approach	Type(s) of competence required	Modelling mode	Types of uncertainty involved	Uncertainty transformation	Method of validation where possible	Specific modelling methods to be employed
Natural system	Scrutinise/ evaluate/ test already existing system	To predict an outcome	Available "objective" data	Quantitative/ Numerical	Calculate/ optimise	Mathematical / math-statistical	Deterministic	None	To eliminate uncertainty	Mathematical/ Logical	Agent Based Modelling
Biological/ ecological system	Adapt/improve already existing system or develop new system to new sector tasks	Propose a specific solution to a well defined problem	Assertions by stakeholders and problem owners	Logical	Simulate	Technical/ Engineering	Stochastic Probabilistic	Probabilistic (RISK)	Reduce option space	Experiment/ experience	System Dynamics Modelling
Technical system	Adapt/improve already existing system or develop new system to new technologies	Provide proposals for alternative possible solutions to a well defined problem	Assertions by external, impartial groups	Graphic	Correlate (Statistically)	Philosophical / Epistemological	Quasi-causal	Genuine (with well defined outcome space)	Specify uncertainly factors	Expert judgement	NLP Non- Linear Programming
Organisational system	Adapt/improve already existing system or develop new system to new social/political/financial environment	To better structure and define a problem	Modellers' own observations, depictions and interpretations	Text/natural language	Compare/asse ss	Sociological/ Organisational/ Behavioural	Logical	Genuine (with ill-defined or unknown outcome space)	Better estimate of probability of outcome	Explicitly none	Linear programming models
Socio-technical system		Increase knowledge and competence within problem area			Describe, shape, give conceptual form	Economics/ finance	Normative	Agonistic	No explicit transformation		Bayesian networks
Conceptual system		To establish and legitimate an idea or a policy direction				Historical Political science					Logic trees
		To provide normative guidelines									Influence diagrams/ Black-box interactive models
											Morphological/ typological
											Narrative & "rich pictures"

Figure 7: Prototype Modelling Assessment Framework (MAF) to be adapted for FORTRESS (see Appendix A for larger diagram).

What is being modelled	Purpose or goal of modelling	Main intended result of the model	From where is principal knowledge derived	Main type(s) of information available	Chief method of approach	Type(s) of competence required	Modelling mode	Types of uncertainty involved	Uncertainty transformation	Method of validation where possible	Specific modelling methods to be employed
Natural systems	Scrutinise/ evaluate/ test already existing system	To predict an outcome	Available "objective" data	Quantitative/ Numerical	Calculate/ optimise	Mathematical / math-statistical	Deterministic	None	To eliminate uncertainty	Mathematical/ Logical	Agent Based Modelling
Biological/ ecological systems	Adapt/improve already existing system or develop new system to new sector tasks	Propose a specific solution to a well defined problem	Assertions by stakeholders and problem owners	Logical	Simulate	Technical/ Engineering	Stochastic Probabilistic	RISK - with well grounded probabilities	Reduce option space	Experiment/ experience	System Dynamics Modelling
Technical systems	Adapt/improve already existing system or develop new system to new technologies	Provide proposals for alternative possible solutions to a well defined problem	Assertions by external, impartial groups	Graphic	Correlate (Statistically)	Philosophical / Epistemological	Quasi-causal	Genuine (with well defined outcome space)	Specify uncertainly factors	Expert judgement	NLP Non- Linear Programming
Organisational systems	Adapt/improve already existing system or develop new system to new social/political/financial environment	To better structure and define a problem	Modellers' own observations, depictions and interpretations	Text/natural language	Compare/assess	Sociological/ Organisational/ Behavioural	Logical	Genuine (with ill-defined or unknown outcome space)	Better estimate of probability of outcome	Explicitly none	Linear programming models
Socio-technical system networks		Increase knowledge and competence within problem area			Describe, shape, give conceptual form	Economics/ finance	Normative	Agonistic	No explicit transformation		Bayesian networks
Conceptual systems		To establish and legitimate an idea or a policy direction				Historical Political science					Logic trees
		To provide normative guidelines									Influence diagrams/ Black-box interactive models
											Morphological/ typological
											Narrative & "rich pictures"

Figure 8: Modelling profile for case-studies modelling for the FORTRESS project.

Appendix 1: Background to General Morphology[*]

The term *morphology* derives from classical Greek (*morphê*) which means *shape* or *form*. Morphology is "the study of form or pattern", i.e. the arrangement and connectivity of parts of an object, and how these “conform” to represent a *whole* or Gestalt. The "objects" in question can be physical (e.g. an organism or an ecology), social/organizational (e.g. an institution or company), or mental (e.g. linguistic forms or any system of ideas).

In Europe, morphology, in the form of combinatorial methods, was used as early as 1290’s by the theologian-logician Ramon Llull (1232-1315) in his *Ars magna* ("The Ultimate General Art"). The first to employ it as a modern modelling method based on cycles of analysis and synthesis was Gottfried Leibniz (1646-1715) in his *De Arte combinatoria* (1666). However, the first to use the term “morphology” as an explicitly defined scientific method would seem to be J.W. von Goethe (1749-1832), especially in his "comparative morphology" in botany. Today, morphology is associated with a number of scientific disciplines where *formal structure* is a central issue, for instance, in anatomy, linguistics, geology and zoology.

In the late 1940’s, Fritz Zwicky, professor of astrophysics at the California Institute of Technology (Caltech) proposed a *generalized form of morphology*, which today goes under the name of General Morphological Analysis (GMA)

> “Attention has been called to the fact that the term *morphology* has long been used in many fields of science to designate research on structural interrelations – for instance in anatomy, geology, botany and biology. ... I have proposed to *generalize and systematize the concept of morphological research* and include not only the study of the shapes of geometrical, geological, biological, and generally material structures, but also to study the more abstract structural interrelations among phenomena, concepts, and ideas, whatever their character might be.” (Zwicky, 1969, p. 34)

Zwicky developed GMA as a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes. He applied the method to such diverse fields as the classification of astrophysical objects, the development of jet and rocket propulsion systems, and the legal aspects of space travel and colonization. He founded the Society for Morphological Research and championed the "morphological approach" from the 1940's until his death in 1974.

Morphological analysis was subsequently applied by a number of researchers in the USA and Europe in the fields of policy analysis and futures studies. In1995-6, working at the Swedish Defence Research Agency (FOI) in Stockholm, advanced computer support for GMA was developed by the author. This has made it possible to create non-quantified inference models, which significantly extends GMA's functionality and areas of application. Since then, some

[*] For a more detailed presentation, see the JORS article:” Problem Structuring with Computer-Aided Morphological Analysis”, downloadable at: http://www.swemorph.com/pdf/psm-gma.pdf.

100 projects have been carried out using GMA, for structuring complex policy and planning issues, developing scenario and strategy laboratories, and analyzing organizational and stakeholder structures.

Essentially, GMA is a method for identifying and investigating the total set of possible relationships contained in a given problem complex. This is accomplished by going through a number of iterative phases which represent cycles of analysis and synthesis – the basic method for developing (scientific) models.

The method begins by identifying and defining the most important *parameters* of the problem complex to be investigated, and assigning each parameter a range of relevant *values* or *conditions*. This is done mainly in natural language, although abstract labels and scales can be utilized to specify the set of elements defining the discrete *value range* of a parameter. (Note that we are using the term *parameter* not in its formal mathematical sense, but in its more general, systems science meaning: i.e. one of a number of factors that define a system and determine its behaviour, and which can be varied in an experiment, including a *Gedanken-experiment*).

A morphological field is constructed by setting the parameters against each other in order to create an n-dimensional configuration space (Figure 1). A particular *configuration* (the black cells in the matrix) within this space contains one ”value” from *each* of the parameters, and thus marks out a particular state of, or possible formal solution to, the problem complex.

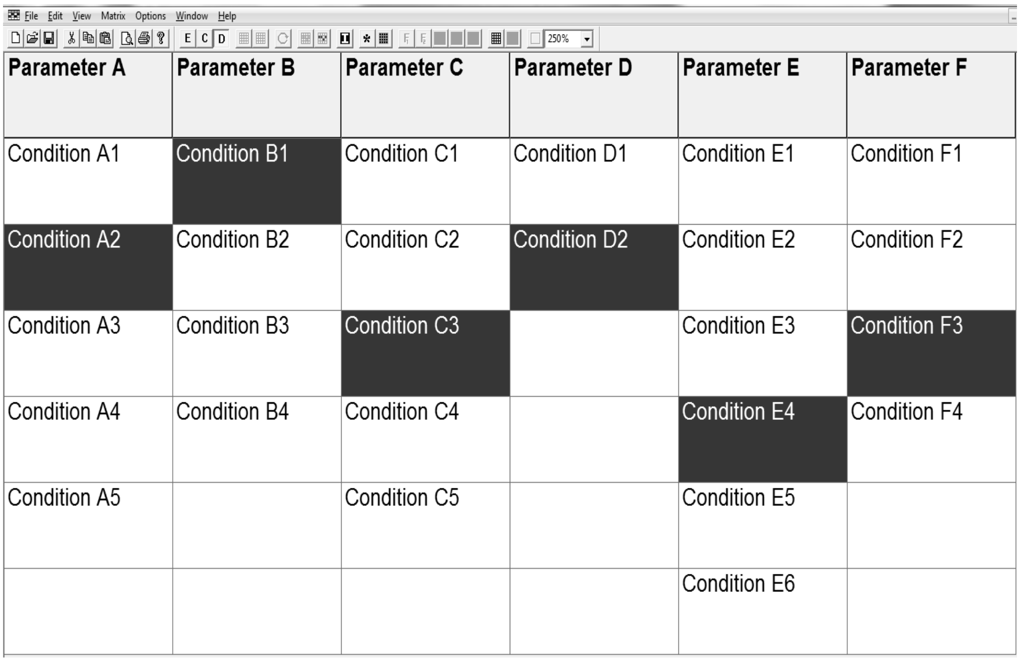

Figure 1: A 6-parameter morphological field. The dark cells define one of 4,800 possible (formal) configurations.

The point is, to examine all of the configurations in the field, in order to establish which of them are possible, viable, practical, interesting, etc., and which are not. In doing this, we mark out in the field a relevant *solution space*. The solution space of a Zwickian morphological model consists of the subset of all the possible configurations which satisfy some criteria. The primary criterion is that of *internal consistency*.

Obviously, in fields containing more than a handful of variables, it would be time-consuming – if not practically impossible – to examine all of the configurations involved. For instance, a 7-parameter field with 6 conditions under each parameter contains almost 280,000 possible configurations.

Thus the next step in the analysis-synthesis process is to examine the *internal relationships* between the field parameters and "reduce" the field by weeding out configurations which contain mutually contradictory conditions. In this way, we create a preliminary outcome or solution space within the morphological field without having first to consider all of the configurations as such.

This “reduction” is achieved by a process of *cross-consistency assessment* (CCA). All of the parameter values in the morphological field are compared with one another, pair-wise, in the manner of a cross-impact matrix (Figure 2). As each pair of conditions is examined, a judgment is made as to whether – or to what extent – the pair can coexist, i.e. represent a consistent relationship. Note that there is no reference here to direction or causality, but only to mutual consistency. Using this technique, a typical morphological field can be reduced by to 90% or even 99%, depending on the problem structure.

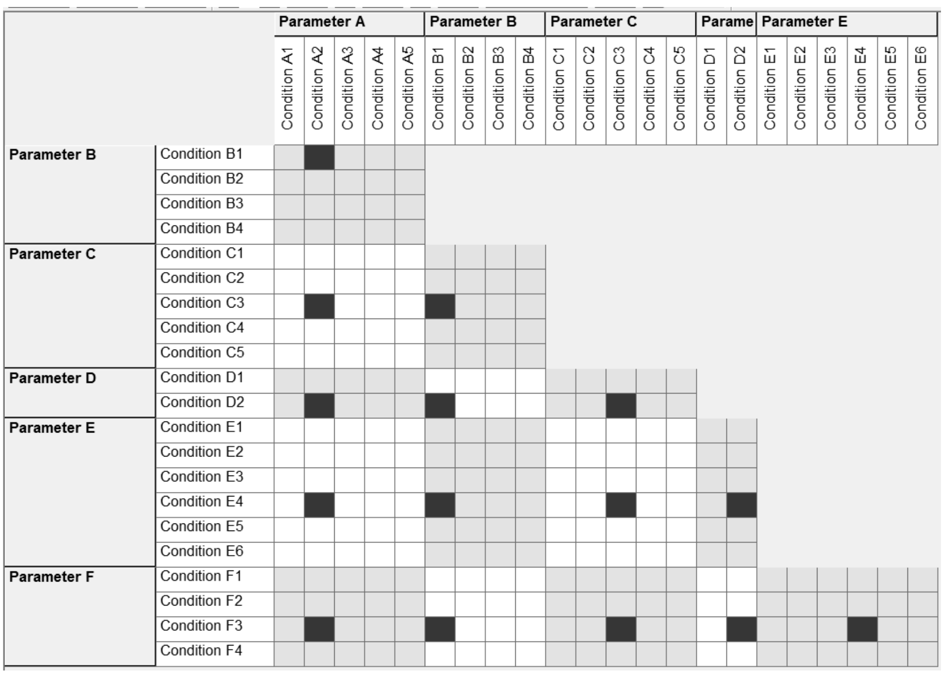

Figure 2: The cross-consistency matrix for the morphological field in Figure 1. The dark cells represent the 15 pair-wise relationships in the configuration given in Figure 1.

There are three principal types of inconsistencies involved in the cross-consistency assessment: purely *logical* contradictions (i.e. "contradictions in terms"); *empirical* constraints (i.e. relationships judged to be highly improbable or implausible on practical, empirical grounds), and *normative* constraints (although these must be used with great care, and clearly designated as such).

This technique of using pair-wise consistency assessments, in order to weed out internally inconsistent configurations, is made possible by the combinatorial relationships inherent in morphological models, or in any discrete configuration space. While the number of configurations in such a space grows "factorially" with each new parameter, the number of *pair-wise relationships between parameter conditions* grows only in proportion to the triangular number series – a quadratic polynomial. Naturally, there are also practical limits reached with quadratic growth. The point is, that a morphological field involving as many as 100,000 formal configurations can require no more than few hundred pair-wise assessments in order to create a solution space.

When this solution (or outcome) space is synthesized, the resultant morphological field function as an *inference model*, in which any parameter (or multiple parameters) can be selected as "input", and any others as "output". Thus, with dedicated computer support, the field can be turned into a laboratory with which one can designate different initial conditions and examine alternative solutions.

GMA seeks to be integrative and to help discover new relationships or configurations. Importantly, it encourages the identification and investigation of boundary conditions, i.e. the limits and extremes of different parameters within the problem space. The method also has definite advantages for scientific communication and – notably – for group work. As a process, the method demands that parameters, conditions and the issues underlying these be clearly defined. Poorly defined concepts become immediately evident when they are cross-referenced and assessed for internal consistency. Like most methods dealing with complex social and organizational systems, GMA requires strong, experienced facilitation, an engaged group of subject specialists and a good deal of patience.

Appendix 2: The initial Project Problem Space (PPS) for project FORTRESS

1. Types of hazards (Natural)	2. Types of hazards (Technical)	3. Types of hazards (Social)	4. Types of hazards (deliberate antagon- istic actions)	5. Geo- graphical level/scope of impact	6. Cross- border status	7. Location	8. Time scale of event/ onset of crisis	9. Impact	10. Sector capacities directly/ primarily affected	11. Sector capacities affected because of primary effects	12. Criticality of components	13. Type of inter- dependency	14. Responsible authorities	15. Coordin- ation levels	16. Warning/ Prediction mechan- isms	17. Disaster cycle	18. Type of disaster response information available	19. Resilience factors	20. Networks involved
Floods	Radiation releases	Mass gatherings	Conven- tional terror attacks	Global	Multiple cross-border	Coast	Sudden (Seconds or minutes)	Single	Transportation GROUND	Transportation GROUND	Major node	Geographic	Police	EU	Prediction/ Forecasting	Mitigation	General sense-making information	Civil protection	Legal
Wildfires	Industrial accidents	Riots	CBRN attacks	International	Single cross-border	Plain	Rapid (Hours/days)	Recurrent	Transportation AIR-WATER	Transportation AIR-WATER	Will create cascade	Physical	Fire	National	Monitoring	Preparation	Geographical info	Crowd sourcing	Financial
Storms/ Snow storms	Transport accidents	Strikes	Cyber terrorism	National	Not cross- border	Hills	Slow (Weeks)	Cyclical	Energy production	Energy production	Used for rescue services	Cyber	Health	Regional	Technical/ administrative warning	Emergency response	Location	NGOs	Logistical
Landslides	Chronic pollution	Rumours	Hostage taking	Regional		Mountain	Creeping (months/years)	Cascading	Energy transmission and distribution	Energy transmission and distribution	Evacuation route	Logical/ functional	Local admin. Municipal govt.	Local	Evacuation	Recovery	Cause of situation	Business continuity	Social
Avalanches	Plant failure	Distrust in government	Insider threats	Local		Rural		Coincident	Water provision	Water provision	Supply route	Social/ communication based	Companies/ industry	Online	No warning	Reconstruction	Recovery time		Administrative
Earthquakes	Urban fires	Polarisation				Urban			Public communication (telecom)	Public communication (telecom)			National security				Who is responsible		
Tsunamis	Building collapse					Metropolitan			Waste & biochem	Waste & biochem			Insurance companies				Who needs info.		
Volcanoes	Dam failure								Healthcare (hospitals&clini cs)	Healthcare (hospitals&clini cs)			Civil protection authorities						
Extreme tempera- tures	Blackouts								Emergency services and national security	Emergency services and national security			MACC, CMC, etc.						
Drought									Economic services	Economic services			Civil society organisation						
Ice storms									Government sector (Decision & continuity)	Government sector (Decision & continuity)			Community based organisations						
Epidemics etc.									Social sector(Educati on, aggregation ic	Social sector(Educati on, aggregation ic			Intergovernme ntal organisations						
Space hazards									Residential housing sector	Residential housing sector									
									Environmental	Environmental									

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