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Deliverable D1.3:
Morphological analysis
Modelling the Project Problem Space

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Contents

1. EXECUTIVE SUMMARY

The aim of FORTRESS is to identify and better understand cascading effects of societal disruptions on critical infrastructure. This will be done 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.

This report – Deliverable 1.3 – describes the development of the first conceptual models of the project's *problem space* using General Morphological Analysis (GMA). It is based on work carried out in two subject-specialist workshops in London in May and July 2014. The *general purpose* of the workshops was to organise structured discussions among project participants and to employ Problem Structuring Methods (PSM) in order to 1) develop among the project participants a common conceptual framework and terminology; 2) to discuss and make recommendations about the structure and bounding of this total project problem space (e.g. as concerns types of infrastructure elements, disruptive events, networks and consequences of disruptions); and 3) to take the initial steps in the iterative design process of developing conceptual models concerning infrastructure interdependence.

One the basis of this work, four specific modelling tasks were initiated which will develop in parallel – and in interaction – with the development with the project as a whole. These are: 1) the development of a *conceptual modelling framework* for the project problem space as a whole, 2) employing a sub-set of this modelling framework to describe and interrelate a number of case studies and scenarios of cascading effects of infrastructure disruptions, 3) carrying out an initial analysis of the relationships between critical infrastructure capacities in order to map out their interdependencies, and 4) the development of a Modelling Assessment Framework (MAF) for identifying and grounding different possible modelling methods which can be employed in the project.

The modelling frameworks presented here are not intended to be *operative models* which will provide actual solutions to the problem of infrastructure disruptions, cascading effects and crisis management. This is the goal of the project as a whole. In this phase of the study, we are developing *conceptual frameworks* which can aid in the development of actual crisis management tools. Moreover, these modelling frameworks will serve as (continually developing) reference points for the project, and can also be seen as an "audit trails" and, if needed, a post-project evaluation tools.

2. INTRODUCTION

> ”Be it through direct connectivity, policies and procedures, or geospatial proximity, most critical infrastructure systems interact. These interactions often create complex relationships, dependencies, and interdependencies that cross infrastructure boundaries. The modeling and analysis of interdependencies between critical infrastructure elements is a relatively new and very important field of study.” (Pederson, et. al. 2006).

This report describes the development of the first conceptual models of the FORTRESS project’s problem space using General Morphological Analysis (GMA). It is based on work carried out in two subject-specialist workshops in London in May and July 2014. The workshops consisted of subject-specialists within the FORTRESS project (including IRKS, TRI TUB, UCL and VRK) representing different areas of knowledge in the project.

The *general purpose* of the workshops was to organise structured discussions among project participants and to employ Problem Structuring Methods (PSM) in order to 1) develop among the project participants a common conceptual framework and terminology; 2) to discuss and make recommendations about the structure and bounding of this total project problem space (e.g. as concerns types of infrastructure elements, disruptive events, networks and consequences of disruptions); and 3) to take the initial steps in the iterative design process of developing conceptual models concerning infrastructure interdependence.

Five specific sub-tasks were imitated and are reported in this deliverable:

1. Developing a prototype *conceptual modelling framework* for the project problem space as a whole which can both integrate the work of the project participants and also serve as an “audit trail” and a post-project evaluation tool (Section 3).

2. Employing a sub-set of the modelling framework to exemplify and inter-relate a number of historic case studies and scenarios of cascading effects of infrastructure disruptions (Section 4).

3. Developing a modelling framework for *cross-border issues* such as impacts, cooperation and planning (Section 5).

4. Carrying out a parameter analysis in order to map the relationships and interdependencies between critical infrastructure capacities given in the modelling framework, and presenting a formal example of how these relationships can be modelled in morphological form (Section 6).

5. Presenting a (meta-) modelling framework for different possible modelling methods which can be used in the project, and how these relate to the modelling tasks at hand, the empirical data available and the uncertainties evolved (Section 7).

All of these sub-tasks involve the use of Problem Structuring Methods (PSM). PSMs are sets of techniques, modelling methods and (often) accompanying software aids, which provide systematic help in framing, structuring and better understanding a given problem complex – often in a group/workshop context.
More specifically, problem structuring methods operate to:

- accommodate multiple alternative perspectives rather than prescribe single solutions,
- function through group interaction and iteration rather than back office calculations,
- generate ownership of the problem formulation through transparency,
- facilitate a graphical (visual) representation for the systematic, group exploration of a solution space,
- focus on relationships between discrete alternatives rather than continuous variables,
- concentrate on possibility rather than probability (see Rosenhead 1996).

For a more general discussion of PSMs see Mingers & Rosenhead (2004). For the use of General Morphological Analysis (GMA) as a PSM, see Ritchey (2006).

The *iterative* steps involved in using GMA as a PSM are:

1. Formulate a focus question concerning what the problem space concerns (i.e. a first rough definition of the problem).
2. Identify the relevant factors i.e. parameters[*] involved
3. Specify the possible states of each parameter
4. Create a morphological (parameter) space
5. Examine the internal relationships between conditions in the parameter space
6. Identify those combinations of factors that are blatantly inconsistent
7. Create Morphological (“if-then”) inference model
8. Generate and compare different solutions or outcomes depending on given initial conditions

At this point, six months into the FORTRESS project, all of the models and conceptual frameworks presented here are prototypes which will be developed in parallel, and in interaction, with the further development of the other Work Packages and with the project in general. Particularly the Project Problem Space (PPS) can be used as an “audit trail” and, if needed, a post-project evaluation tool.

[*] Note that we are using the term “parameter” not its formal mathematical sense, but in its more general *systems science* sense: i.e. one of a set of factors that defines a system and determines its behaviour – and which can be varied in an experiment (including a *Gedankenexperiment*).

3. INITIAL PROJECT PROBLEM SPACE

The initial problem structuring process began by discussing the *Focus Question* to be used as a basis for the first phase of this process. After a group discussion, the following focus question was formulated:

> 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 (first prototype) problem space (Table 3.1).

Table 3.1 List of preliminary parameters for the problem space modelling framework.

1. Types of hazards (Natural)
2. Types of hazards (Technological)
3. Types of hazards (Social)
4. Types of hazards (Antagonistic)
5. Geographical level/scope of disruption
6. Cross-border status
7. Location of primary disruption
8. Time scale of event
9. Impact (mode of...)
10. Sector capacities directly/primarily affected
11. Sector capacities affected because of primary impacts
12. Criticality of infrastructure/capacity components
13. Type of interdependencies
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

Consequence parameters such as negative4 and positive effects of disruptions were also considered, but it was decided that these will be taken up separately in a later modelling session.

When these significant parameters are identified, each is broken down into a range of relevant *values* or *states*. The sum total of the parameters and their ranges of states define a parameter space which is called a *morphological field*. It is this morphological field which is the basis for the conceptual modelling framework for the project problem space presented in Figure 3.1.

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&clinics)	Healthcare (hospitals&clinics)			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(Education, aggregation, ic	Social sector(Education, aggregation, ic			Intergovernmental organisations						
Space hazards									Residential housing sector	Residential housing sector									
									Environmental	Environmental									

Figure 3:1: First iteration prototype morphological field for FORTRESS project problem space.

The field shown in Figure 3.1 is the initial (unbounded) problem space developed during the first workshop meeting for Work Package 1. Its scope may be larger than the *actual project problem space* that will 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 will take place once the maximal problem field is scrutinised by all of the partners in the in the FORTRESS project.

The choice of parameters was brainstormed by the working group, in order to represent the main variables within the problem space. However, the initial *value ranges* that have been given to these parameters are temporary and under development, as there was not always a consensus within the working group concerning *how these ranges should be expressed*. This is due to different stakeholder positions and scientific disciplines/research perspectives. (When possible, these value ranges have been taken from the international Crisis Management (CM) literature, in order to be more readily recognisable for different stakeholders.) One of the purposes of the problem structuring process is to create a dialogue between different subject-specialists and stakeholders (e.g., academics, decision support specialists and practitioners) in order to find a common language and terminology for the concepts being structured. This process must develop over time in an iterative manner.

Below is a short commentary on the 20 parameters initially identified in the two workshops:

Parameters 1-4. Type of hazards

All four hazard "modes" are included here: natural, technological, social and antagonistic. This gives a total of 33 types of hazards. It remains to be discussed if the project can/shall potentially treat all of these types, or if the list should be bounded.

Parameter 5 . Geographical level/Scope

The "values" of this parameter were taken from the international litterateur, but there are problems here. We may need to break the parameter into two: a. Geographical scope and b. whether the scope is cross-border or not. The general feeling was to try to formulate this as a single parameter in order to save "modelling space".

Parameter 6. Cross-border status

Defined *ad hoc.*

Parameter 7. Location

Taken from international hazard and disaster literature.

Parameter 8. Time scale of event/ onset of crisis

Taken from international hazard and disaster literature.

Parameter 9. Impact

Imprecise term where parameters values are still blurred or overlapping. Needs to be better defined and exemplified: What are we trying to identify here?

Parameter 10. Sector capacities directly (primarily) affected by the hazard

At first, it was proposed to use the United Nation's definition of critical facilities. According to this definition e.g. fire brigade is part of the critical infrastructures. However, the question arose: Are we talking about interdependencies of *critical infrastructures,* or *social functions*, or *social sectors*?

The workshop participants pointed out that there are differences between a societal capacity, vulnerable objects and infrastructures. A "sector" is just the way to organize this, and it was suggested that we use tins term to include infrastructure. It was thus agreed upon to start out by talking about "impact on ***sector capacities***" (even though we realise that, in the case of complex infrastructures such as the communication infrastructure, it will be difficult to generalize impacts because the infrastructure is so broad and all encompassing.)

Twelve initial sector *capaciti*es selected here were abstracted from the critical infrastructure inventory presented in FORSTESS D1.1 (2014). They were chosen in order to develop the prototype interdependency model (see Section 6).

Parameter 11. Sector capacities indirectly affected because of primary effects

Whereas parameter 9 concerns capacities that are directly affected by a given hazard, this list of (identical) sector capacities concerns the "secondary" effects i.e., capacities affected *as a consequence of the primary effects*. This cascading process could be further iterated, but we decided to map only primary and secondary effects in this initial modeling space. Further iterations may be necessary in "time-dependent" models.

Parameter 12. Criticality of components

This parameter has to do with dependency associated with the function and use of infrastructure, but needs to be more thoroughly defined and exemplified.

Parameter 13. Type of interdependency

This parameter has to do with what the interdependency is based upon.

Parameter 14. Responsible authorities

Taken from the international literature on CM.

Parameter 15. Coordination levels of CM

Taken from the international literature on CM.

Parameter 16. Warning/ Prediction mechanisms

Taken from international hazard and disaster literature and CM literature.

Parameter 17. Disaster cycle

Taken from international hazard and disaster literature and CM literature. This parameter will be useful when developing time dependent case studies and scenarios

Parameter 18. Type of disaster response information available

Taken from the international hazard and disaster literature, but this needs to be better defined and expanded.

Parameter 19. Resilience factors

Needs to be better defined, integrated and expanded.

Parameter 20. Networks involved

Needs to be better defined, integrated and expanded.

4. MODELLING FRAMEWORK FOR CASE STUDIES AND SCENARIOS

Work Package 3 (sub-tasks 3.1 and 3.2 and their associated deliveries) will present nine case studies in which disasters and emergencies have taken place, in order to illustrate cascading or cross-border effects, including mapping networks of systems and actors. In this context, one can use a subset of the parameters of the Project Problem Space in order to profile, describe and compare the case studies, and later, the scenarios to be developed.

A prototype *case study modelling framework* was developed in a 1-day workshop in London with TRI and RCAB, to be employed as a part of D3.1 and D3.2. Here we demonstrate the concept and show how it can be used, with example case studies.

The parameters chosen for the case study model are:

Table 4.1: Parameters of case study modelling framework

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 (a new *ad hoc* parameter for this model)

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 4.1: Examples case study profile for Firework factory explosion (2000) – Netherlands.

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 4.2: Comparison of example case study “Firework factory explosion” (FFE) and “Avalanche Disaster of Galtür” (ADG). Light blue is only FFE; middle blue is only ADG; dark blue is the overlap between.

Figure 4.1 shows the prototype case study modelling framework with the example of “Fireworks factory explosion (2000) – Netherlands” (FFE), and industrial accident with high physical impact and cross-border effects.

Figure 4.2 shows a comparison between two case studies, the “FFE” example and the Avalanche Disaster of Galtür (ADG), in Austria in 1999. Here we see the light blue cells representing is only FFE; the middle blue cells representing ADG only; and the dark blue cells representing the overlap between the two.

When all of the case studies – plus the proposed scenarios – are added to the model, they can easily be scrutinised and compared – as in Figure 4.2.

5. MODELLING FRAMEWORK FOR CROSS BORDER ISSUES

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

For a first prototype modelling framework, 6 parameters have been identified (Table 5.1). This framework will initially be used to situate the structure of cross-border CM activities and resources involved in the 9 case-studies to be put forward D3.1.

Table 5.1: Parameters for cross-border issues

1. Areas of cross-border impacts
2. Areas of cross-border cooperation
3. Types of cross-border activities/agreements
4. Extent of cross-border planning
5. Types of cross-border assistance & cooperation during disaster
6. Scope of cross-border cooperation

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 5.1: Prototype modelling framework for cross-border issues.

6. MODELLING CRITICAL INFRASTRUCTURE DEPENDENCY

The next step in this first iteration of the modelling process is to ascertain how the different parameters are related to one another as concerns mutual influence and dependence. This is done with Weighted Influence Diagrams (WIDs) using an “influence matrix”.

WIDs interrelate a number of different factors, parameters or variables (terms which, in this context, are generally interchangeable) in order to analyse the cross-impact or cross-influence relationships obtaining between them. This is done on the basis of both (empirical) case studies and informed judgements among subject specialists. (See APPENDIX D for a description of the method.) The analysis allows one to make a relative determination of which variables are:

“Drivers” (strongly influencing but not strongly influenced)
“Passive” (strongly influenced but not strongly influencing)
“Critical” (both strongly influenced and strongly influencing)
“Buffers” (neither strongly influenced nor strongly influencing)

The first steps in the process of mapping societal interactions and interdependencies is 1) the identification of a preliminary set of relevant modelling parameters or variables, and 2) the investigation of the relationships between these parameters in order to ascertain their mutual influence and interdependence. This is variously termed a parameter analysis, driver analysis or sensitivity analysis, and is carried out with Weighted Influence Diagrams (WIDs).

WIDs interrelate a number of different parameters (factors or variables) in order to analyse the cross-impact or cross-influence relationships obtaining between them. (See Addenda D for a description of the method.) Note that, *at this juncture*, both the choice of the modelling parameters and the judgements made about their mutual connectivity are intended to *test the utility of the modelling methods*, not to address the *empirical validity of the input data*. This latter issue will be addressed in a later stage in the project.

Twelve initial parameters representing ***critical sector capacities*** were selected at the “macro-level” in order to develop the prototype interdependency model. (In columns 10 and 11 in Figure 3.1 the “values” *residential housing* and *environment* were added on after this dependency model was developed.) The parameters were abstracted from the critical infrastructure inventory presented in FORTRESS D1.1 (2014).

The twelve capacities chosen were:

1. Transportation (Ground: Road and rail)
2. Transportation (Air-Water)
3. Energy production
4. Energy transmission and distribution
5. Water provision
6. Public communication
7. Waste & biochemical treatment
8. Healthcare (hospitals & clinics)
9. Emergency services and national security
10. Economic/Financial services
11. Government sector services
12. Social sector services

These parameters were then treated as nodes in a directed, cyclic graph (digraph), a.k.a. a non-quantified Influence Diagram. Figure 6.1 shows the initial (first-round) judgements made in order to model the interconnectedness between the 12 nodes given above:

- **1** = The parameter in the left hand column has a **direct** causal influence on the given parameters (listed by their respective numbers) in its adjacent row. (The number "1" is arbitrary here, and is simply a software technical matter.)

- **BLANK** = There is no direct influence from the left hand column to the given parameter.

The assessments are made from each row on the left column, to each of the numbered columns on the adjacent right. For example, disruptions in "Ground transportation" (1) are seen as having a direct effect on "Air-Water transportation (2) – as shown in the red-marked cell in Figure 6.1. Here we are only dealing with *direct influence*, and we are not concerned with the *relative strengths* of these respective influences.

Figure 6.2 is a representation (on the basis of these judgments) of the complex web of connections between the parameters. In itself it does not give a great deal of information, except to show the highly connected, non-linear nature of this system of variables. However, we can display certain significant features of this interconnectedness. Figure 6.3 shows one of the four variables that directly influences all of the other variables: *Ground Transportation*. (The other three are *Energy Production and Distribution* and *Public Communication*.) Figure 6.4 shows the *mutual causal feedback loops* between *Ground Transportation* and six other variables.

Wirkung VON / AUF	1	2	3	4	5	6	7	8	9	10	11	12	Su.E
1. Transportation (ground)		1	1	1	1	1	1	1	1	1	1	1	11
2. Transportation (air-water)	1		1				1	1	1				5
3. Energy production	1	1		1	1	1	1	1	1	1	1	1	11
4. Energy transmission and distribution	1	1	1		1	1	1	1	1	1	1	1	11
5. Water provision			1				1	1	1	1	1	1	7
6. Public Communication	1	1	1	1	1		1	1	1	1	1	1	11
7. Waste _biochem			1	1	1			1		1	1	1	7
8. Healthcare (hospitals..)		1							1			1	3
9. Emergency services/ homeland sec.	1	1					1	1		1	1	1	7
10. Economic/financial services	1	1	1	1		1		1			1	1	8
11. Government (decision/continuity)						1			1			1	3
12. Social infrastructure						1		1	1		1		4
Summe Beeinflussung	6	7	7	5	5	6	7	10	9	7	9	10	

Figure 6.1: Cross-influence matrix for the 12 chosen parameters. 1 = directly influencing; Blank = not directly influencing.

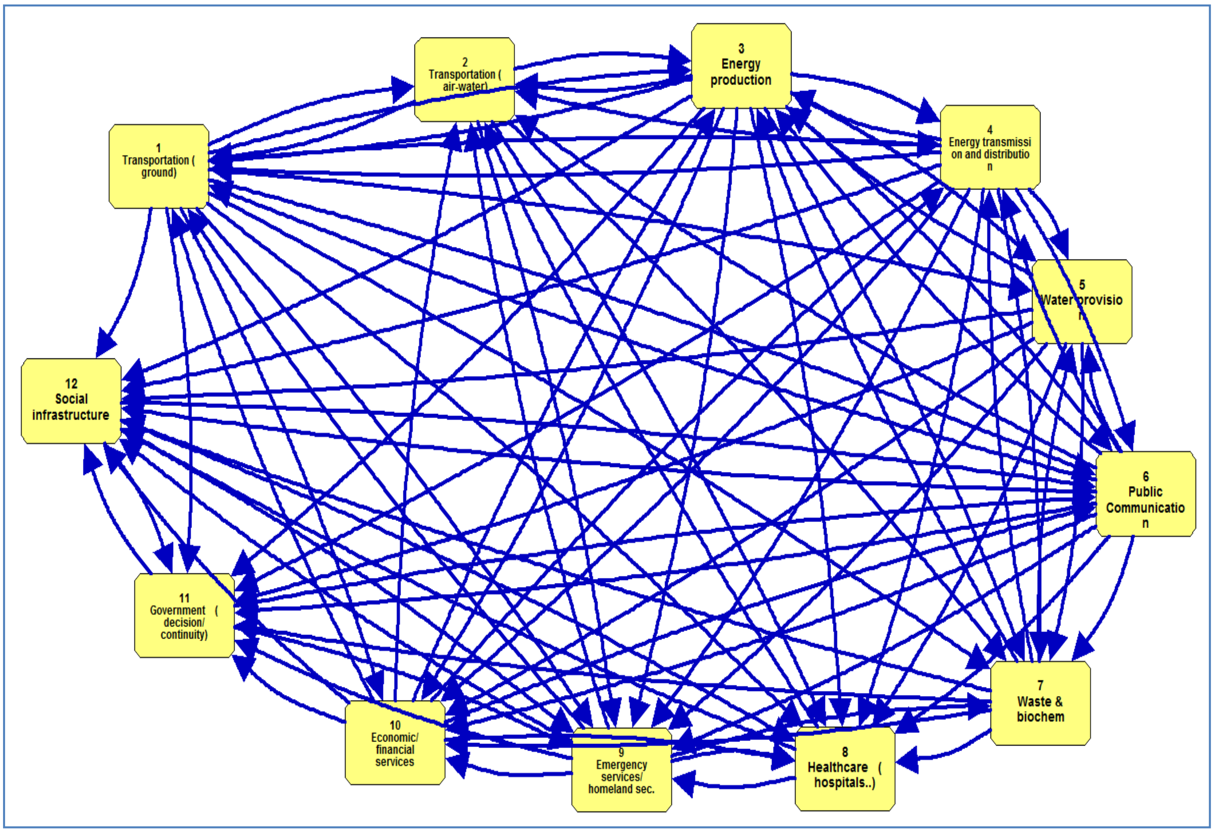

Figure 6.2: Mutual influence between nodes in a directed, cyclic graph.

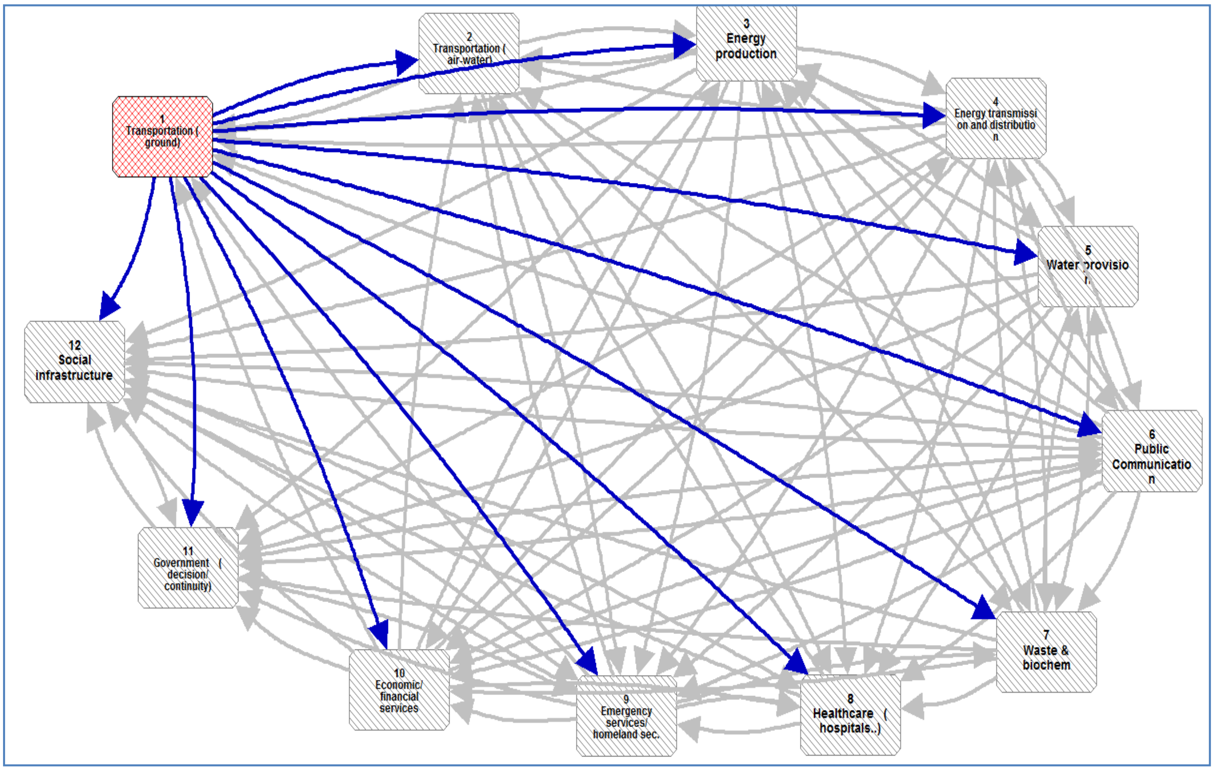

Figure 6.3: Ground transportation shown as directly influencing all other capacities

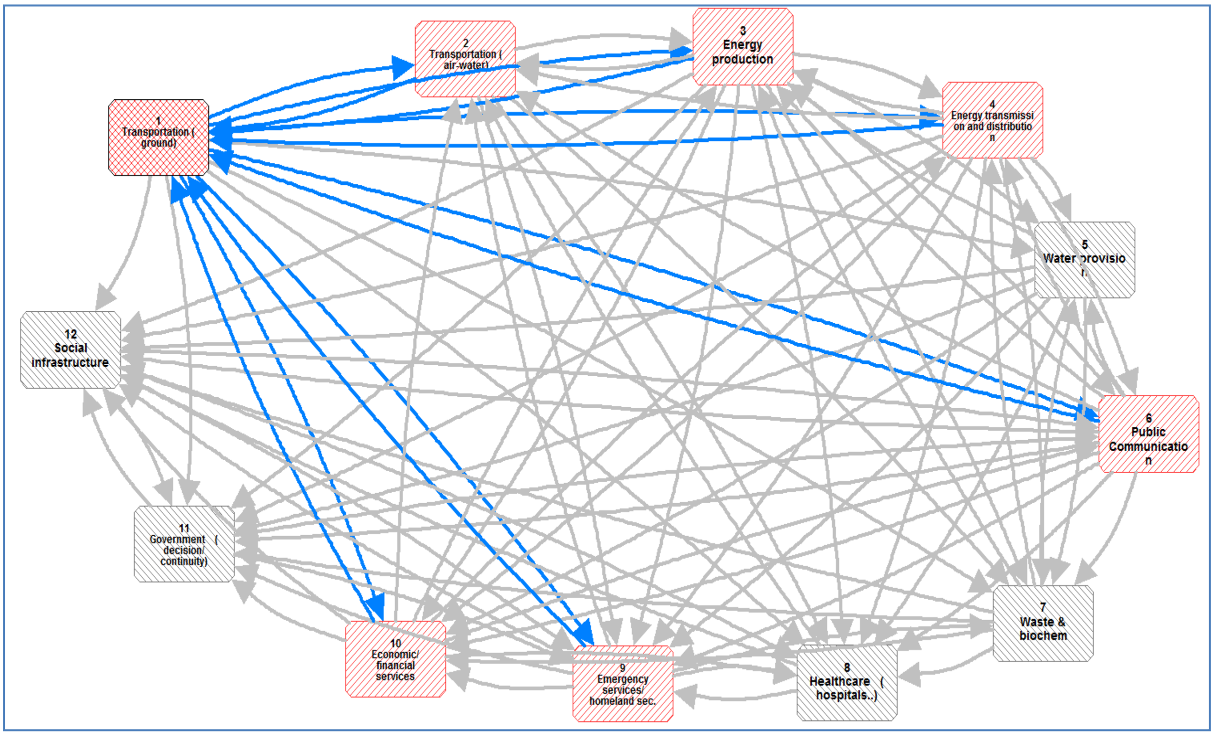

Figure 6.4: Mutual causal feedback loops between Ground Transportation and six other variables (2, 3, 4, 6, 9 & 10).

The next step is to introduce weights into the mutual connection between variables, thus creating a Weighted Influence Diagram (WID). Introducing weights to the connective assessments allows one to ascertain a relative determination of which variables are, relatively speaking, *Drivers*, *Passive*, *Critical* or *Buffers*.

Wirkung VON / AUF	1	2	3	4	5	6	7	8	9	10	11	12	Su.E
1. Transportation (ground)		2	2	1	1	1	2	3	2	2	2	3	21
2. Transportation (air-water)	2		2				3	1	2				10
3. Energy production	3	3		3	3	3	3	3	2	3	2	2	30
4. Energy transmission and distribution	3	3	3		3	3	3	3	2	3	2	2	30
5. Water provision			2				2	3	1	1	1	2	12
6. Public Communication	2	3	1	2	1		1	3	2	1	2	2	20
7. Waste _biochem			1	1	2			2		1	1	2	10
8. Healthcare (hospitals..)		1							2			2	5
9. Emergency services/ homeland sec.	2	3					1	2		1	1	2	12
10. Economic/financial services	1	1	2	1		1		1			1	1	9
11. Government (decision/continuity)						1			2			1	4
12. Social infrastructure						1		1	1		1		4
Summe Beeinflussung	13	16	13	8	10	10	15	22	16	12	13	19	

Figure 6:5. Weighted cross-influence matrix for the 12-parameters.

Figure 6.5 shows the weights of the cross-influence relationships as estimated (as a first approximation) by the working group. The weightings were done row by row with a 4 point scale from 0-3:

3 = Has a crucial DIRECT influence on …
2 = Has a significant DIRECT influence on …
1 = Has some (or a little) DIRECT influence on ...
BLANK = Has NO DIRECT influence on …

Figure 6.6 shows the relative influence relationships between the parameters based on these weightings. Here we see that energy provision, ground transportation and public communication are the strongest drivers, whereas healthcare and social infrastructure are those most sensitive to influence. With these weightings, the relative effects of the disruption of any particular infrastructure capacity on the other 11 capacities can also be represented. An example of the is shown in Figure 6.7, which shows the relative influence of the disruption of ground transportation on the other 11 parameters.

In principle, these influences can be iterated step-wise to show second, third, etc. order cycles of influence – although this is hardly numerically reliable. Influence diagrams are blunt instruments, intended to be used as first conceptualisations, not as numerical simulations.

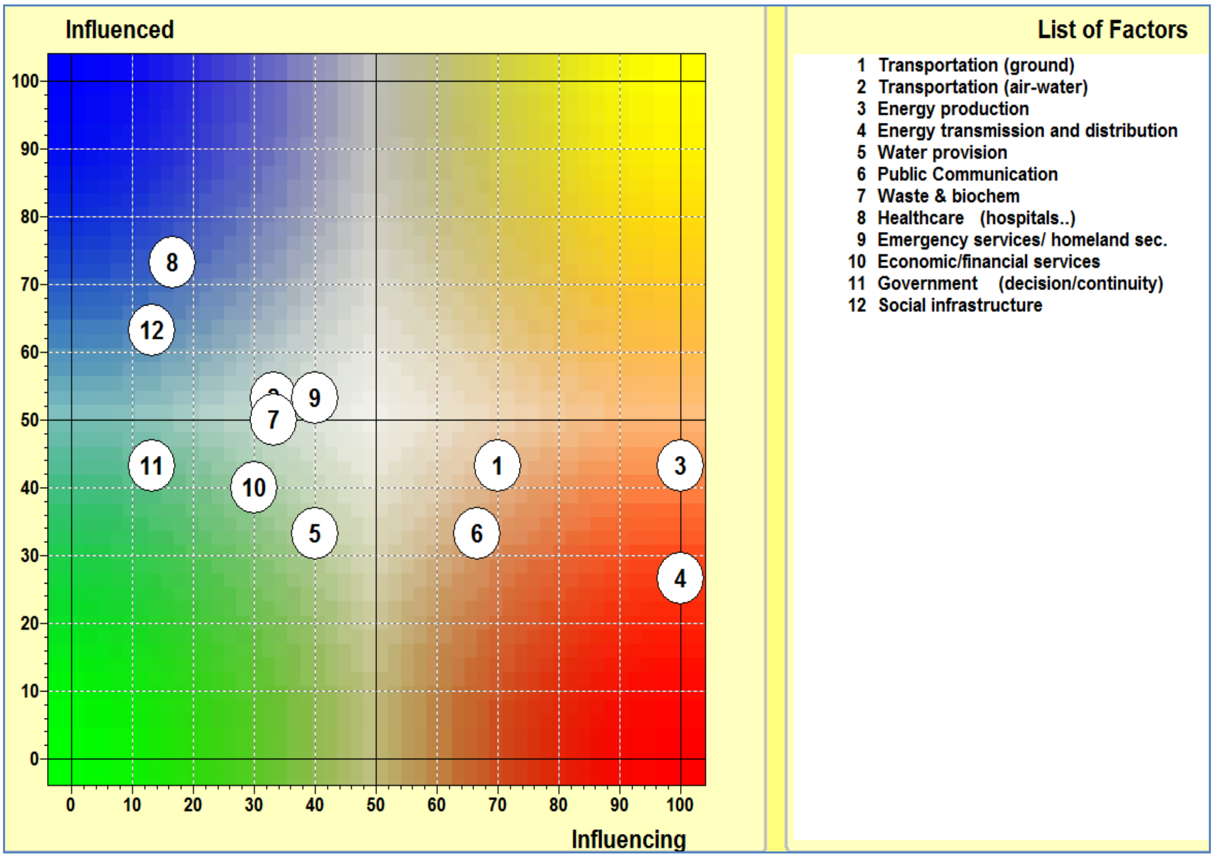

Figure 6.6: Relative influence relationships between the parameters. Energy provision, ground transportation and public communication are the strongest drivers, whereas healthcare and social infrastructure are the most sensitive to influence.

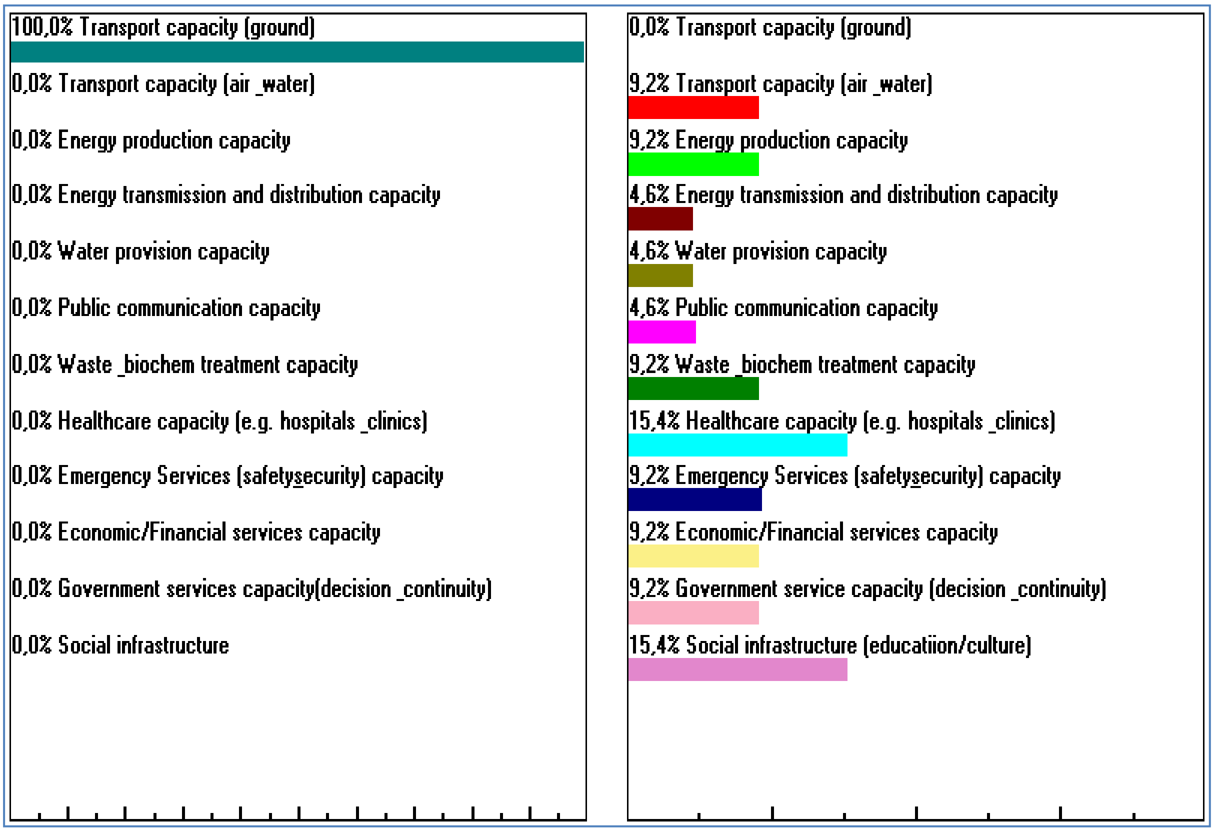

Figure 6.7: Relative effects of major ground transport disruption on the other 11 infrastructure capacities.

At this point, the question was put forward concerning how “people” fit into the scheme of things: i.e. how is the “general public” affected, and how would they, in turn, influence the system as a whole? It was thus suggested that we add to the parameter list “General public”, in the sense of a societal capacity. Added into the analysis, Figure 6.8 shows this supplementary parameter taking a “critical” position of being highly influenced, but also influencing the total system.

In this context, it is instructive to compare these results with a study of *social function interdependency* done at the Swedish Defence Research Agency in Stockholm in the early 2000’s (in a workshop facilitated by the author – but unpublished). Figure 6.9 shows one of the WIDs produced in this study, with its (somewhat similar) list of 14 parameters.

Firstly, we can see the similarity between these two studies concerning the relative importance of *energy provision*, *communications*, *public transport* and *water provision*. However, the parameters that stand out here are those of “Labour power” in the Stockholm model, and “General public” in the London workshop model – both “critical”. It would be interesting to see how the “General public” parameter in the London model would have positioned itself if it had, instead, been termed “Labour force”.

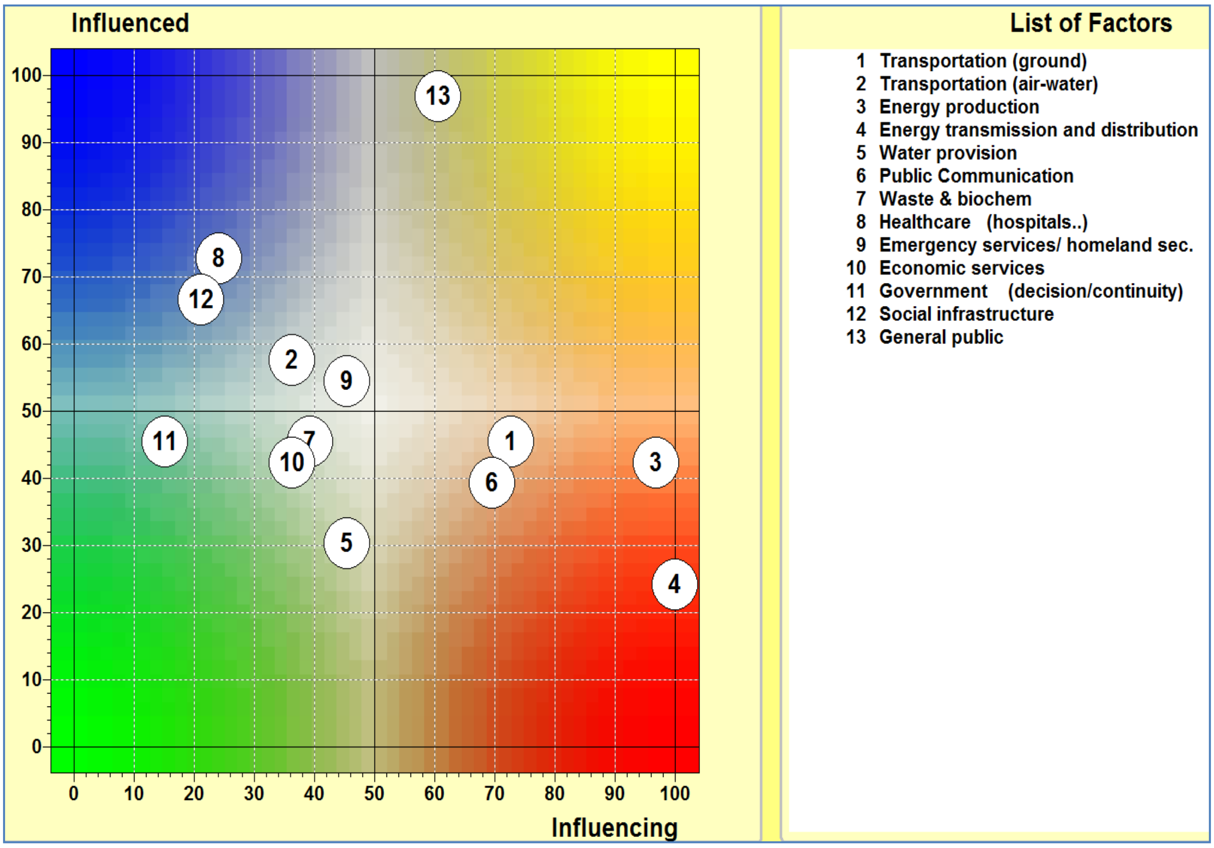

Figure 6.8: Critical position of the supplementary variable "General public" (parameter 13) in the London model.

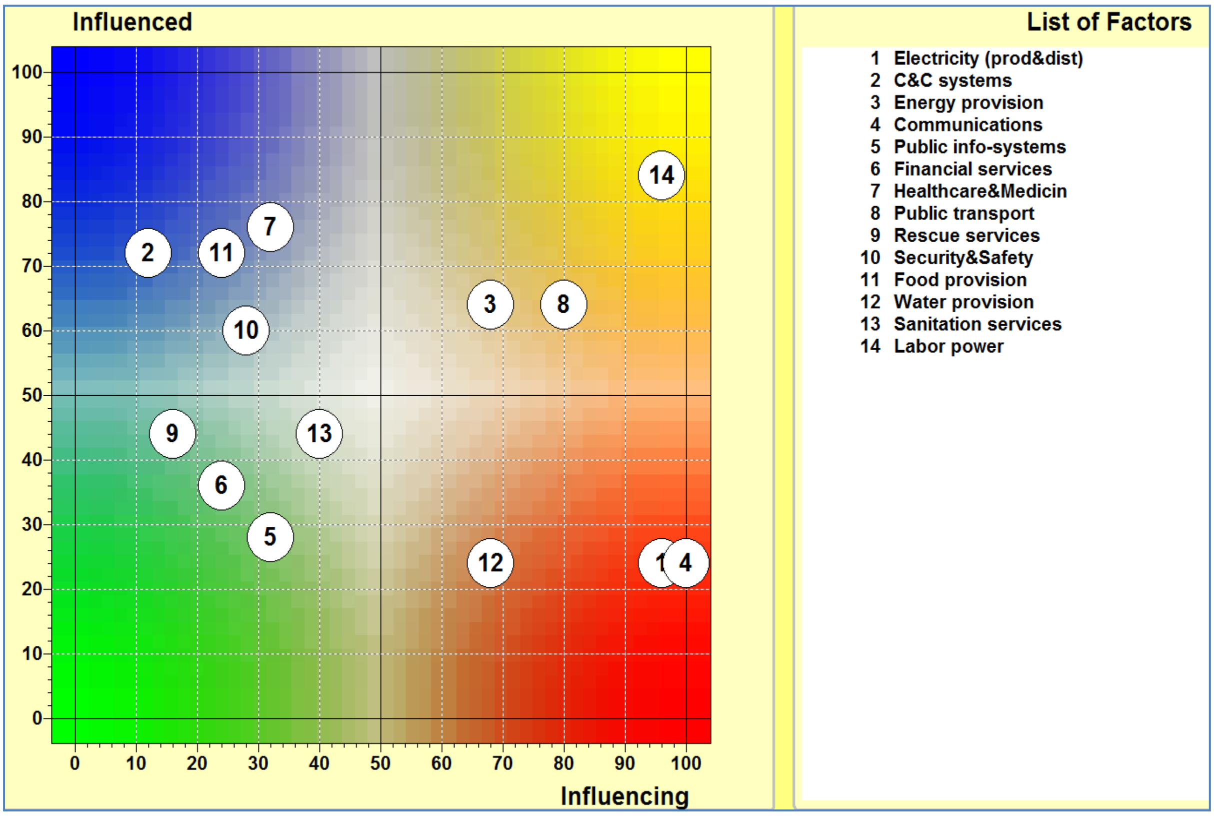

Figure 6.9: Stockholm study showing the variable "Labour power" as critical.

Figure 6.10 (below) shows how the sector capacity interdependence model might look in the form of a morphological model. This type of model will also be explored later in the project.

Transportation infrastructure	Energy infrastructure	Water infrastructure	Food infrastructure	Waste & Hazardous materials infrastructure	Healthcare infrastructure	Emergency services infrastructure	Finance infrastructure	Government infrastructure	Social infrastructure
Rail Infrastructure	Energy production capacity (power plants etc.)	Water Infrastructures (Including water pumps)	Food production capacity	Hazardous waste facilities	Infectious disease/poisoning centres	Coordination centres	Companies of particular strategic values (e.g. Main headquarters, critical information)	Decision centres at national and local level	Icon sites
Road Infrastructure	Transmission and distribution infrastructure	Waste water treatments plants	Food distribution capacity	Hazardous chemical facilities	Hospitals	Operative Centres (eg. Police Stations, Fire brigades)	Banks, financial institutions	Continuity, Archives and data centres	Schools and Universities
Aviation Infrastructure	Storages, production and main pipelines	Dams and reservoirs	Food storage and warehousing capacity	Hazardous bio facilities	Emergency centres/clinics	Logistics and Emergency shelters	xxx	xxx	Community Centres (places were local identity is made, aggregation values
Shipping infrastructure	xxx	xxx	Food supply centres	xxx	xxx	xxx	xxx	xxx	Churches and Faith Centres
Intermodal capacity	xxx	xxxx	xxx	xxx		xxx			Environmental sites
		xxxx	xxx			xxx			

Figure 6.10: Example of 10 sector capacity interdependence model in morphological format.

7. A "MODELLING ASSESSMENT FRAMEWORK"

Analyzing and modelling complex social, technical and organisational systems presents us with a number of difficult methodological problems. Firstly, many of the variables involved are difficult to quantify in a meaningful way as they contain strong social, political and cognitive dimensions. Secondly, the uncertainties inherent in such problem complexes often cannot be fully described or delineated. This includes both so-called *agonistic uncertainty* (conscious, self-reflective actions among actors) and non-specified uncertainty associated with future scientific discoveries, open systems and emergent processes.

Finally, social systems are extremely non-linear in that literally everything interacts with everything else; where many of the variables act as both causes and effects; and where the parametric relations between variables are continually shifting in unpredictable ways. We are essentially working with a complex, evolving n-body problem which has no analytical "modelling solutions".

This means that employing mathematical (functional) modelling and/or numerical simulation, in an attempt to predict how things are actually going to "work out" is, at present, out of the question. 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 in social-technical systems.

These include the problems of *covariate sufficiency* (not being able to identify and include all the relevant variables needed to account for the phenomenon under investigation) and *spurious relationships* between identified variables due to this non-closure (i.e. when exogenous, non-observed variables, which can influence the identified modelling variables, are themselves correlated). (See Holland, 2006; Roy & Mohapatra, 2007; Russo, 2010; Ritchey, 2011, 2012).

However, the methodological intractability of simulating societal interdependency, in hopes of actually predicting the course or outcomes of cascading effects of societal disruptions, 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 operational planning, awareness building, training and instruction, and possibly as 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), cyclic influence diagrams (WIDs)
3. General Morphological Analysis (GMA)
4. Bayesian Network Models (BNM)
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 are necessary prerequisites for the more “complex” ones. In this report, we have exemplified method 1, 2 and 3. Methods 4, 5 and 6 will be treated in later reports.

The choice of modelling method(s) depends on the nature of the modelling task, including, for example, the nature of the “object” being modelled, the type of empirical information available concerning this “object”, and the nature of the uncertainties involved. Here we give an example of how a meta-modelling framework can be developed in order to scrutinise how different modelling methods can be used in the FORTRESS project.

The prototype Modelling Assessment Framework (MAF) presented here is developed from a number of studies done at the Swedish Defence Research Agency (Stockholm) during the 2000’s concerning how modelling methods in Operations Research (OR) were employed for different modelling tasks, under different constraints, and for different forms of uncertainty (Ritchey, 2014).

The prototype meta-modelling framework contains the following parameters.

Table 7.1: Parameters for the Modelling Assessment Framework

1. What is being modelled
2. Purpose or goal of modelling
3. Main intended final result
4. From where is principal knowledge derived
5. Main type(s) of information 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 employed

Figure 7.1 shows the 12-parameter morphological field representing the Modelling Assessment Framework (MAF). Figure 7.2 is an example of a modelling profile defined in the field, representing the task of modelling case-studies of infrastructure disruptions and cascading events.

This initial framework needs to be refined and adapted for the specific requirements and conditions of the FORTRESS 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 7.1: 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 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 7.2: Modelling profile for case-studies modelling

8. APPENDIX A: PROTOTYPE MORPHOLOGICAL FIELDS

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 A.1: Case study and scenario template

Transportation infrastructure	Energy infrastructure	Water infrastructure	Food infrastructure	Waste & Hazardous materials infrastructure	Healthcare infrastructure	Emergency services infrastructure	Finance infrastructure	Government infrastructure	Social infrastructure
Rail Infrastructure	Energy production capacity (power plants etc.)	Water Infrastructures (Including water pumps)	Food production capacity	Hazardous waste facilities	Infectious disease/poisoning centres	Coordination centres	Companies of particular strategic values (e.g. Main headquarters, critical information)	Decision centres at national and local level	Icon sites
Road Infrastructure	Transmission and distribution infrastructure	Waste water treatments plants	Food distribution capacity	Hazardous chemical facilities	Hospitals	Operative Centres (eg. Police Stations, Fire brigades)	Banks, financial institutions	Continuity, Archives and data centres	Schools and Universities
Aviation Infrastructure	Storages, production and main pipelines	Dams and reservoirs	Food storage and warehousing capacity	Hazardous bio facilities	Emergency centres/clinics	Logistics and Emergency shelters	xxx	xxx	Community Centres (places were local identity is made, aggregation values
Shipping infrastructure	xxx	xxx	Food supply centres	xxx	xxx	xxx	xxx	xxx	Churches and Faith Centres
Intermodal capacity	xxx	xxxx	xxx	xxx		xxx			Environmental sites
		xxxx	xxx			xxx			

Figure A.2. Example of 10 sector capacity interdependence model in morphological format.

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 A.3. Modelling Assessment Framework (MAF) to be adapted for FORTRESS

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 A.4. Prototype modelling framework for cross-border issues.

9. APPENDIX B: OVERVIEW OF GENERAL MORPHOLOGICAL ANALYSIS

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

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 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 (Zwicky 1966, 1969). 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 operational analysis, policy analysis and futures studies (e.g. (e.g. Godet, 1994; Rhyne 1995; Coyle & McGlone, 1995; Ritchey 1997). In 1995, advanced computer support for GMA was developed, This has made it possible to create interactive, non-quantified inference models, which significantly extends GMA's functionality and areas of application (Ritchey, 2011). Since then, some 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 or “configurations” 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 (Ritchey, 1991).

The method begins by identifying and defining the most important dimensions (or *parameters*) of the problem complex to be investigated, and assigning each dimension a range of relevant

[*] For a list of projects, see http://www.swemorph.com, u/Project List

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.

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 darkened 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.

Parameter A	Parameter B	Parameter C	Parameter D	Parameter E	Parameter F
Condition A1	Condition B1	Condition C1	Condition D1	Condition E1	Condition F1
Condition A2	Condition B2	Condition C2	Condition D2	Condition E2	Condition F2
Condition A3	Condition B3	Condition C3		Condition E3	Condition F3
Condition A4	Condition B4	Condition C4		Condition E4	Condition F4
Condition A5		Condition C5		Condition E5	
				Condition E6	

Figure C:1: A 6-parameter morphological field. The darkened cells define one of 4800 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 field consists of the subset of all the 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 6-parameter field with 6 conditions under each parameter contains more than 46,000 possible configurations. Even this is a relatively small field compared to the ones we have been applying.

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 is achieved by a process of *cross-consistency assessment*. 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 up to 90 or even 99%, depending on the problem structure.

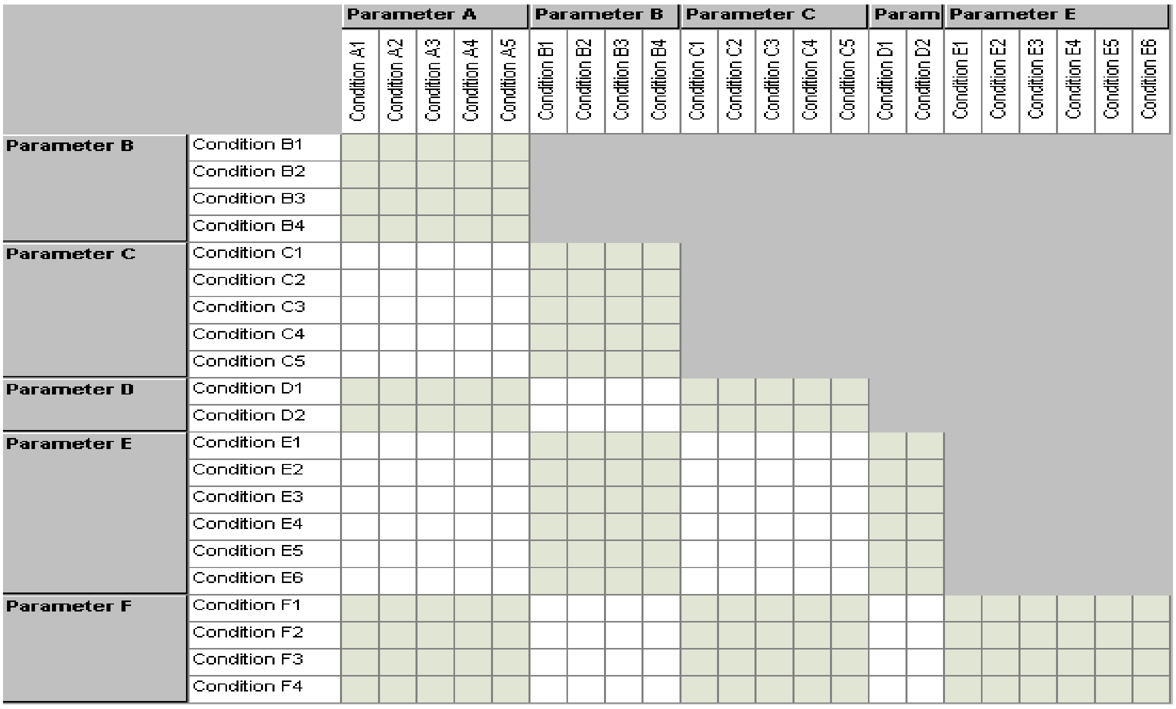

Figure C:2: The cross-consistency matrix for morphological field in Figure 1.

There are three principal types of inconsistencies involved here: purely *logical* contradictions (i.e. those based on the nature of the concepts involved); *empirical* constraints (i.e. relationships judged 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 between conditions, in order to weed out internally inconsistent configurations, is made possible by a principle of dimensionally inherent in morphological fields, or any discrete configuration space. While the number of configurations in such a space grows exponentially 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, however, is that a morphological field involving as many as 100,000 formal configurations can require no more than few hundred pair-wise evaluations in order to create a solution space.
When this solution (or outcome) space is synthesized, the resultant morphological field becomes 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 initial conditions and examine alternative solutions.

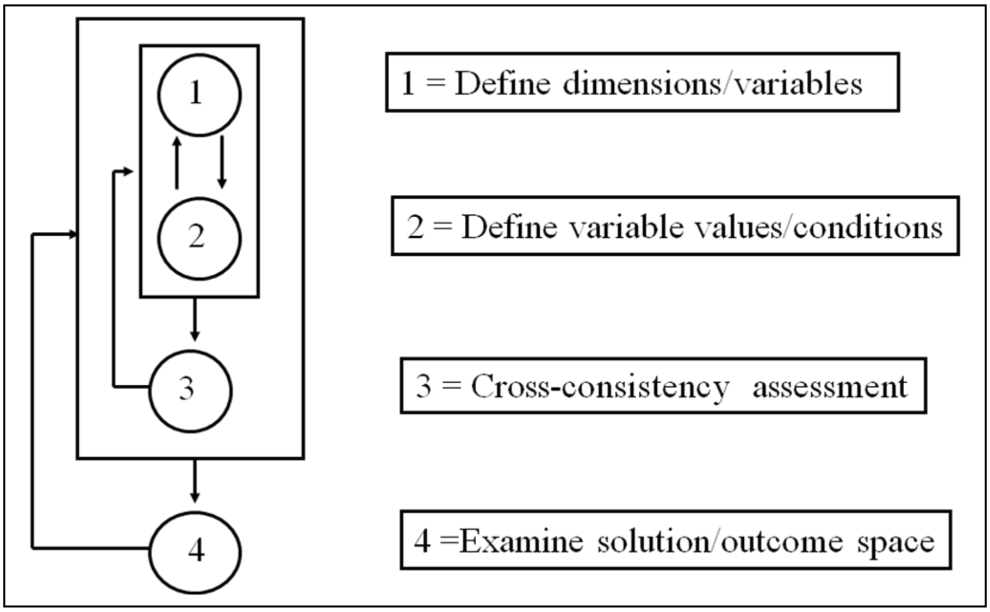

Figure C:3: The iterative phases of a morphological analysis

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.

10. APPENDIX C: FORMAL PROPERTIES OF MORPHOLOGICAL MODELS

1. The morphological field

Let N = number of parameters in a morphological field (in the Reference field, figure 1, N=5) and let P denote a Parameter such that the parameters in a morphological field are:

$$P_1, P_2, P_3 \ldots P_N$$

Let v_x = the number of conditions in the value range of a given parameter P_x, such that the total morphological field is (quantitatively) defined by:

$$\{P_x v_i\}_{x,i}$$

Then, the total number of *simple configurations* T_{SC} (i.e. a configuration with *one and only one condition designated under each parameter*) in a morphological field is:

$$T_{SC} = \quad v_1 * v_2 * v_3 \ldots v_N$$

or

$$T_{SC} = \prod_{i=1}^{n} v_i$$

This simply shows that T_{SC} increases in a *factorial* manner with the increase in the number of parameters "N". So much for the basic morphological field.

P1	P2	P3	P4	P5
P_1V_1	P_2V_1	P_3V_1	P_4V_1	P_5V_1
P_1V_2	P_2V_2	P_3V_2	P_4V_2	P_5V_2
P_1V_3	P_2V_3	P_3V_3	P_4V_3	P_5V_3
P_1V_4		P_3V_4		P_5V_4

Figure C:1: Reference morphological field where N=5

2. The Cross-consistency matrix and Parameter blocks

The Cross-consistency matrix (CCM) pairs off every condition in each parameter with every other condition in all the other parameters. A *parameter block* (PB) consists of all of the paired conditions between two parameters, cross-referenced in the form of a 2-dimensional typology. In Figure 2, the parameter blocks are shown in alternating shaded and white groups.

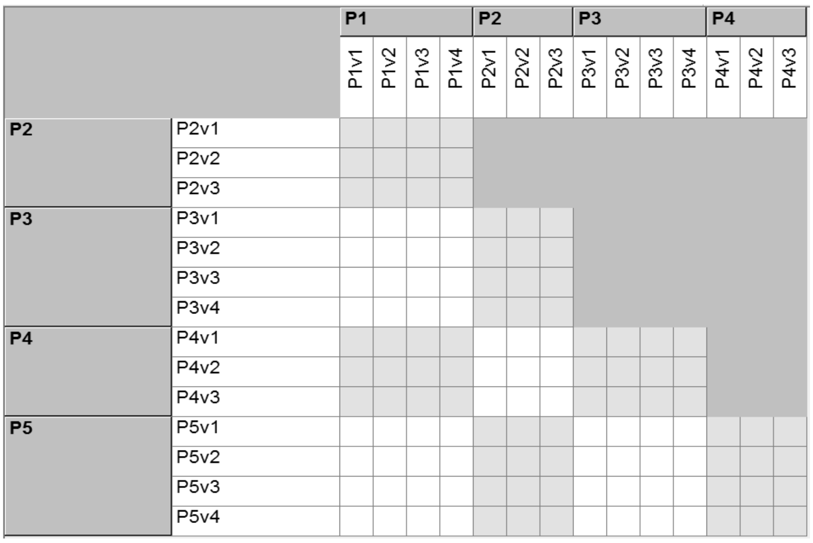

Figure C:2: Cross-consistency matrix (CCM) for morphological field in Figure 3.

If N = number of parameters in a morphological field, then the number Parameter Blocks in the field's Cross-Consistency Matrix is:

$$\tfrac{1}{2}N\ (N-1)$$

This is an interesting mathematical expression that pops up all over that place. For instance:

- It is the formula for generating the triangular number series
- It is the possible number of (non-directed) edges connecting N nodes in a graph.
- It is taught in social network theory and in facilitator training as the number of communication channels or possible (two-person) dialogues between N participants in a workshop (which is why group dynamics changes dramatically at around 7-8 people).

Of course, all this has a common base: Generally, ½N(N-1) is the number of dyadic (pair-wise) relationships between N elements or objects. It is equal to the binomial coefficient:

$$ {}_{n}C_{k} \equiv \frac{n!}{(n-k)!\,k!} $$

when $k = 2$.

Also, ½N(N-1) is central to the discussion of any metric space: it is *the number of coefficients (or functions of position) required to define the metric properties of a space of N dimensions*.(Riemann, 1953).

Number of cross-consistency pairs

If the number of parameters in a morphological model is N and the number of parameter values for a parameter P_x is v_x, then the number of dyadic (pair-wise) relationships (Ct) between *all parameter values* (and thus the total number of cells in the cross-consistency matrix – CCM) is:

$$Ct = \sum_{i=1}^{n-1} \sum_{j=2}^{n} v_i \cdot v_j$$

The take-home message is this: that while the number of formal configurations in a morphological model increases "geometrically" (factorially) with each additional parameter, the number of cross-consistency pairs increases "only" in proportion to the quadratic polynomial f(x)=½x(x-1). This is what makes it possible to employ Cross-Consistency Assessment (CCA) to reduce a relatively large problem space to a more manageable solution space, without having to examine every configuration in the problem space. To sum up: we have four magnitudes which determine the primary formal properties of a morphological model:

N	= number of parameters
½N(N-1)	= number of parameter blocks in the CCM
ΣΣ vv	= number of pair-related cells in the CCM
Π v	= total number of simple configurations in the model

In the case of v = 4 for each of the parameters, the relationship between these magnitudes is:

a	*b*	*c*	*d*
N	½N(N-1)	$\sum_{i=1}^{n-1} \sum_{j=2}^{n} v_i \cdot v_j$	$\prod_{i=1}^{n} v_i$
Number of parameters	Number of dyadic relationships between parameters blocks	Number of CCM cells	Number of simple configurations
2	1	16	16
3	3	48	64
4	6	96	256
5	10	160	1024
6	15	240	4096
7	21	336	16348
8	28	448	65536
9	36	576	262144

Table C:3. The primary formal properties of a morphological model (for v=4)

3. The relationships between form and content

Three ratios

Expressions *b*, *c* and *d* (Table 1) are formally determined by N and V_x, i.e. the number of parameters and the number of conditions under each of the parameters. There are three other quantities that are determined by the *logical, empirical and normative judgements* made in the Cross-Consistency Assessment (CCA) which, together with *b*, *c* and *d*, give rise to three ratios that can help us to formally "type" morphological models.

These three ratios are:

1. The ***connectivity quotient (κ - Kappa)***: The ratio of the number of parameters blocks *which are constrained* (PBc) to the *total* number of parameter blocks ½N(N-1). This is analogous to how the dimensions of an abstract space are topologically connected.

2. The ***consistency quotient*** (**χ -** χῖ */Chi*): The ratio of the number of *mutually constrained parameter value pairs* in the Cross Consistency Matrix (CCM) to the *total number of parameter value pairs* (or *cells*) in the CCM.

3. The ***solution space quotient_*** **(ϛ -** *Stigma***)**: The ratio of the number of simple configurations in the *solution space* to the number of simple configurations in the in the *total problem space*.

3.1 Connectivity Quotient (κ - Kappa)

Connectedness in a morphological model concerns how the different *dimensional constructs* of the model (i.e. its parameters) "hang together", i.e. are topologically connected. There are two (principal) possibilities here for each of the ½N(N-1) parameter pairs: either two given parameters contain mutual (logical and/or empirical) *constraints*, or they are (logically and/or empirically) *orthogonal*.

The *Connectivity Quotient* **κ** is the ratio of the number of *constrained parameter blocks* (PBc) to the *total number of parameter blocks* ½N(N-1).

$$\kappa = \frac{PBc}{\frac{1}{2}N\,(N-1)}$$

Since the minimum number of Constrained Parameter Blocks (PBc) required in order to define a proper model is (N-1), then the possible range of PBc is:

$$(N-1) \rightarrow \tfrac{1}{2}N(N-1)$$

and where **κ** ranges from: $2/N \rightarrow 1$

3.2 The Consistency Quotient (χ) (Chi)

The *consistency quotient* is the ratio of the number of mutually constrained (i.e. inconsistent) cells (Cx) in the Cross-Consistency Matrix (CCM) to the total number of cells (Ct) in the CCM.

$$\chi = Cx/Ct$$

where Ct = $$\sum_{i=1}^{n-1} \sum_{j=2}^{n} v_i \cdot v_j$$

The number of pair-wise mutually constrained cells (Cx) in a cross-consistency matrix is determined by the judgements made by the *subject specialist group* doing the morphological modelling. It is an "empirical" input, in the sense that it is not determined by any formal properties of the model. Rather, it is determined by the explicit or implicit *nature of the concepts* supplied in order to create the model. In order to determine Cx**,** one simply has to count them in the CCM.

3.3 The Solution space quotient (ς = Stigma)

The *solution space quotient* ς is the ratio of the number of simple configurations making up the *solution space* ($Config_{sol}$) to the total number of (formal) simple configurations in the in the *problem space*.

$$\varsigma = Config_{sol} \ \textbf{[divided} \prod_{i=1}^{n} v_i$$

This ratio is a crucial indicator of the nature of the model thus developed. If, for instance, the ratio expressed by ς is near or equal to 1, then the model is hyper-coherent. This means that just about everything is consistent with everything else. There is nothing wrong with such models; they are simply telling us that practically everything is possible. Certain types of futures scenarios models are of this form. If, on the other hand, ς is very small, then the model is hyper-constrained, meaning that very few model configurations are possible.

11. APPENDIX D: WEIGHTED INFLUENCE DIAGRAMS (WIDS)

The term *influence diagram* is used to describe a number of modelling techniques. In general, an influence diagram is a graphical model of a system which depicts influence relationships between different elements or nodes of the system, shows the direction of such influences and (usually, but not always) allows for feedback loops or circular causality (i.e. a cyclic graph). In some cases, influences can be given relative strengths, and flows between nodes can be mapped. In other cases, the diagrams are only pictorial representations of complex nets of interaction. In all cases, the variables (or nodes) in influence diagrams are treated a "black boxes" – i.e. their internal states are not specified.

Weighted influence diagrams (WIDs) show the *relative* strengths of influences between those variables within the diagram what are considered to influence each other. With this information, WIDs can be manipulated mathematically in order to identify and present certain properties of the interrelations between variables.

WIDs are employed for modelling systems which are too complex and uncertain for full-out functional/mathematical modelling (e.g. System Dynamics Modelling), or – where such functional/mathematical modelling *is* appropriate – as a precursor for identifying the relevant variables and approximating their inter-relationships.

The inter-relationships between the variables/nodes of a WID are mapped out on an inference matrix – a.k.a. a cross-impact matrix (Figure 1) and worked out by calculating *influence indices*. The methodological of calculating these indices is described in Cole (2006):

> "An influence matrix is a square matrix with identical factors in the same rank order in rows and columns. The matrix is constructed by using a scoring strategy to quantify the strength of influence of row factors on individual column factors on an element by element scoring basis. It is possible to rank the row and column factors using row (1) and column (2) sum scores as derived below. By contrast the factor typology is produced by mathematically combining the row and column sum scores to produce multiplier (5) and quotient scores (4).
>
> Assume that we have an influence matrix (M_{ij}) of dimensions 15 rows by 15 columns. To evaluate this matrix we sum the rows (i) and columns (j) of the influence matrix to calculate the row (active) (1) and column (passive) sums (2).
>
> $$\text{Row (or active) sum (RS)} = \sum_{i=1}^{i=15} M_{ij} \qquad (1)$$
>
> $$\text{Column (or passive) sum (CS)} = \sum_{j=1}^{j=15} M_{ij} \qquad (2)$$
>
> As a refinement of the solution method of Vester (1978), the factor typology is calculated using three lines of numerical information. First, we calculate the absolute numerical difference (AND) between the RS and CS scores for each factor. This additional step is not included in the method of Vester (1978, 2002) or Vester and von Hesler (1982) who have concentrated on interpreting a factor typology continuum rather than being concerned with factor typology groupings. Both these approaches have their merits. We place more importance on grouping to decide on functional character as a basis for system dynamic

modelling. The AND score helps discriminate between buffer/critical and passive/active factors with intermediate passive and active sum scores.

$$\text{Absolute Numerical Difference (AND)} = RS - CS \quad (3)$$

For a particular factor, if AND is close to zero, the functional character of that factor tends towards critical or buffer. In contrast, a higher AND score indicates the functional character of that factor tends towards passive or active.

The quotient score is used to identify whether a particular factor is active or passive:

$$\text{Quotient Score (QS)} = AS\,/\,PS \quad (4)$$

High quotient scores (i.e. where the row sum is much larger than the column sum for that factor) indicate active functional character, meaning a strong influence on other factors. A low quotient score indicates passive functional character in which the factor is relatively more strongly influenced by other factors compared with the strength of its influence on other factors. Factors with intermediate quotient scores will tend to be more critical or buffering in functional character.

The multiplier score is used to identify whether a factor is critical or buffer:

$$\text{Multiplier Score (MS)} = AS \text{ x } PS \quad (5)$$

High multiplier scores indicate critical functional character, meaning a strong influence on other factors and strongly influenced by other factors. Low multiplier scores indicate buffering functional character in which the factor is weakly influenced by other factors and has a weak influence on other factors. Factors with intermediate multiplier scores will tend to be more passive and active in functional character. In both cases, we use the AND score to decide borderline cases." (Cited from Cole, 2006).

The principal result of a WID is to show the relative difference between variables along these lines:

- Variables that strongly influence other variables, but are not strongly influenced: **Drivers**
- Variables that are strongly influenced other variables, but do not strongly influence: **Passive**
- Variables that both strongly influence other variables, and are strongly influenced: **Critical**
- Variables that are neither strongly influenced, nor strongly influence: **Buffers**

In order to demonstrate these relationships, we take simple example of four variables, with the following name/properties:

1. Variable 1: High output – High input
2. Variable 2: High output – Low input
3. Variable 3: Low output – High input
4. Variable 4: Low output – Low input

Wirkung VON / AUF	1	2	3	4	Su.E
1. High output - High input		1	9		10
2. High output - low input	9		1		10
3. Low output -- high input	1				1
4. Low output - Low input					0
Summe Beeinflussung	10	1	10	0	

Figure D:1: Influence matrix

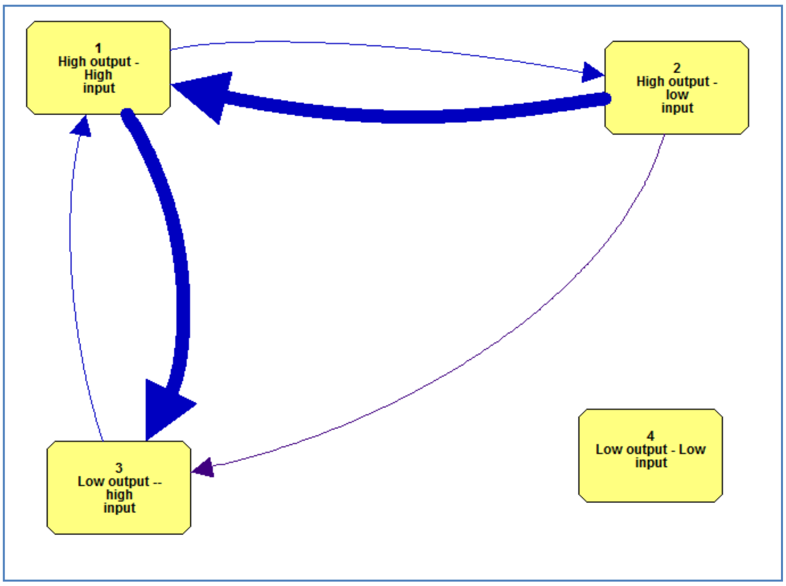

Figure D:2. Graphical representation

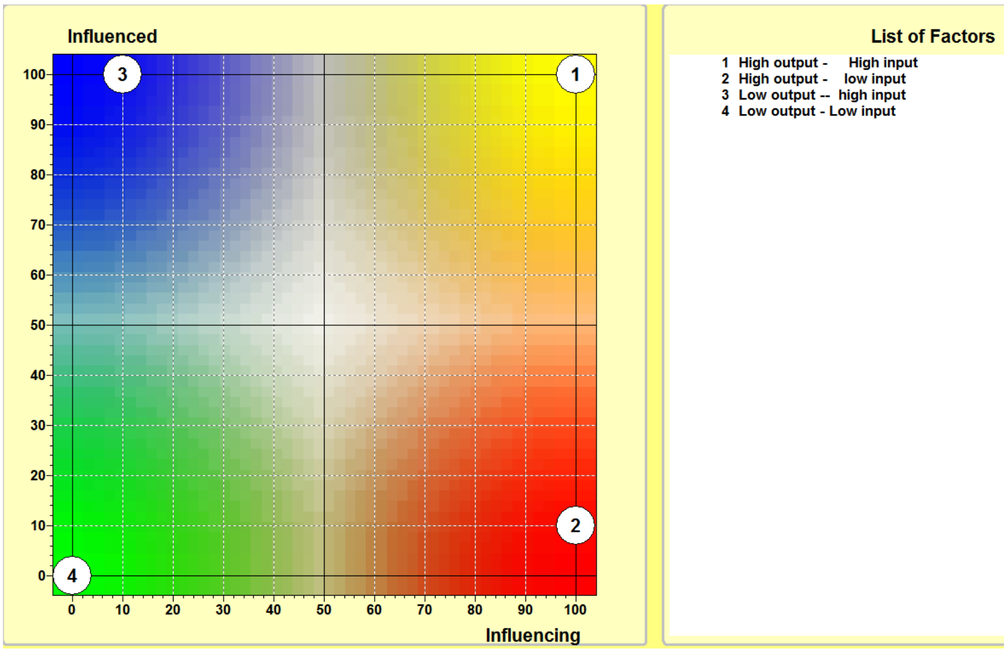

Figure D:3. Influence diagram for influence matrix in Figure D:1.

12. APPENDIX E: MA/CARMA SOFTWARE VIEWER INSTRUCTIONS

Carma_Viewer requires no special installation. Simply copy the two Carma CCA-Viewer files (and any accompanying files) to a suitable directory. If you have received a Carma.zip-file, copy it to a suitable directory and unzip it. The password is: **Plato.** Double click on the Carma icon to open the Viewer. The password is also: **Plato**. Click on the "Open file" icon in the menu and open the Carma model-file (extension: .scn) that you wish to run, as you would with any other Windows program.

Engage (click in) the -cluster-toggle button (if it is not already engaged). This activates the entire configuration list (without this toggle IN, only one configuration is shown at a time). You can then treat any parameter (i.e. column) as an independent variable (e.g. as a driver) by clicking on any of its values, to see what values of the remaining parameters are valid for that driver value. Values from different parameters can be activated concurrently. Also, more than one value in a single parameter can be activated by holding the CTRL-key down and clicking on different values.

To initially examine how the morphological field behaves, click through all the values of all the fields one at a time. Minimum and maximum field output for each parameterized value (if these "K" judgments have been included in the model) can be obtained with the ∗ -toggle button. Button-out gives the minimum field output; button-in gives maximum field output.

The "Freeze" button freezes a particular configuration, on order to compare it with others. (Logical AND, OR, XOR features, and path diagnostics, are not available on this Viewer)

Those cells which contain a red dot in the upper right corner have text in their scratchpad areas. Placing the mouse pointer over a cell (both in the D- and C- matrices) and right-clicking will access the scratchpad area.

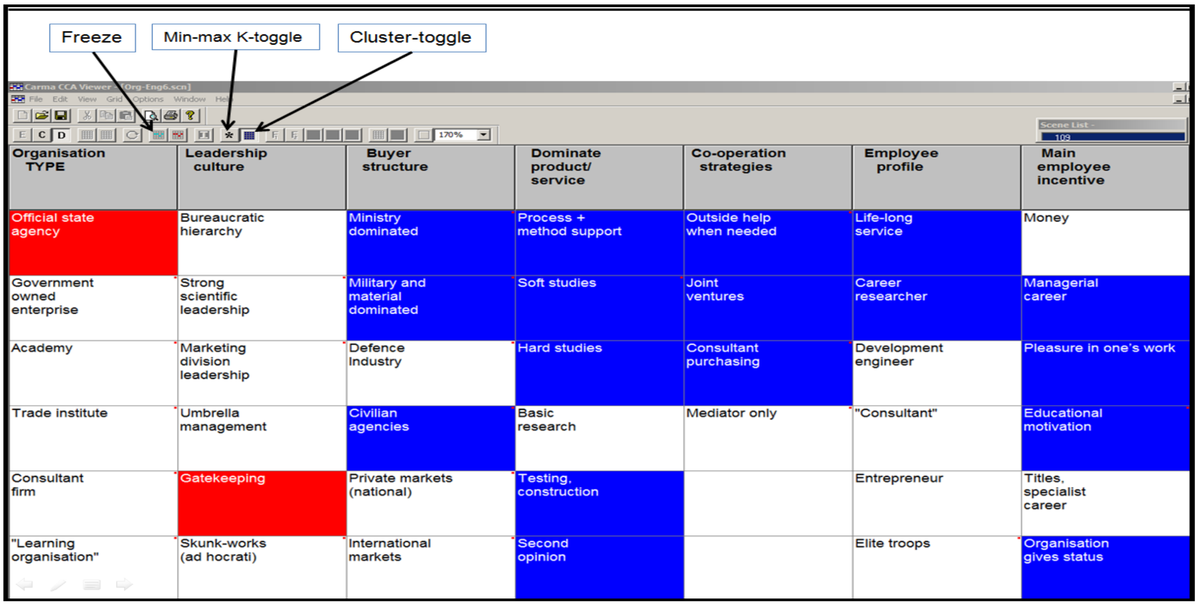

Figure E:1. Morphological model with two input parameters (red) selected as drivers and clustered output (blue)

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