Acta Morphologica Generalis *Vol. 4 No. 2 (2015)*

ISSN 2001-2241

Principles of Cross-Consistency Assessment in General Morphological Modelling

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Abstract: In General Morphological Analysis (GMA), the Cross-Consistency Assessment (CCA) both serves as a check on the integrity and clarity of the concepts being employed, and allows us to identify and weed out all internally incompatible relationships in order to reduce the total *problem space* of the morphological field to a smaller, internally consistent *solution space*. With computer support this solution space can be treated as an inference model. This article examines the methodological principles and practical procedural issues involved in the CCA process, and presents examples from a number of client-based projects.

Keywords: general morphological analysis, cross-consistency assessment, modelling theory, synthesis phase of modelling, inference by exclusion.

NOTE: This was intended to be the *second* article concerning the two basic phases of GMA: "Parameter formulation" and "Cross-Consistency Assessment". However, matters got complicated and this article is now appearing first. The reason for this is that the methodological principles of parameter formulation in GMA involve such basic modelling theoretical issues – especially the issue of *orthogonality* – that it has required more time to research than I had originally expected. Fortunately, the basic methodological principles of CCA are not directly dependent on parameter formulation *per se*, so that this article can stand on its own.

1. Introduction

As with all scientific modelling, General Morphological Analysis (GMA) is based on an iterative process involving cycles of *analysis* and *synthesis* (Ritchey, 1991, 2012a). In the analysis phase, parameters (i.e. variables and their respective domains) are formulated which represent the model's initial *problem space*. In the synthesis phase, connective relationships between parameters are defined. In the case of GMA, these relationships are expressed in terms of *mutual constraints* between category variables. Such constraints are identified and assigned through what is called a Cross-Consistency Assessment (CCA).

It is important to note that, as a *process*, the CCA both serves as a check on the integrity and clarity of the concepts being employed, and facilitates a deep dive into the nature of the problem space being studied. However, the end-purpose of the CCA is to identify and weed out all internally contradictory or otherwise incompatible relationships, in order to find the set of *internally consistent* configurations representing a *solution space*. With proper computer support, such a solution space can be treated as an inference model, which is one of the principal goals of the GMA modelling process.

This article presents the methodological principles involved in the CCA, as well as a summary description how the CCA procedure is actually carried out. A number of examples from client-based projects are presented. We begin with a recap of the formal properties and combinatorics involved in the CCA (a more detailed presentation of the formal properties of morphological models *in general* can be found in Ritchey, 2012b).

NOTE: For those not previously acquainted with GMA, things will make more sense if you read one of the basic articles on the subject first. See e.g. Ritchey (2006a), which is available for download at the designated URL.

2. Formal properties of the Cross-Consistency Assessment

Parameters and configurations

Let P denote a *parameter*[*] and let N = *number of parameters* in a morphological field (in Figure 1, N=5). Let v_x = the number of states or *values* in the value range of a given parameter P_x. Then, the total number of *simple configurations* T_C (i.e. a configuration with one and only one value designated under each parameter) in a morphological field is:

$$T_C = v_1 * v_2 * v_3 \ldots v_N$$

or

$$T_C = \prod_{i=1}^{n} Vi$$

This simply shows that the number of simple configurations increases in an exponential (or *factorial*) manner with the increase in the number of parameters N.

P 1	P 2	P 3	P 4	P 5
P1v1	P2v1	P3v1	P4v1	P5v1
P1v2	P2v2	P3v2	P4v2	P5v2
P1v3	P2v3	P3v3	P4v3	P5v3
P1v4	P2v4	P3v4		P5v4

Figure 1: A five parameter morphological field with 4x4x4x3x4 = 768 possible "simple" configurations, one shown in black.

[*] 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 *Gedankenexperiment*.

Cross-Consistency matrix and parameter connectivity

The Cross-Consistency Matrix cross-references the value ranges of each *pair of parameters*. Each cross-referenced pair is called a *parameter block* (PB) and takes the form of a 2-dimensional typology. In Figure 2, the parameter blocks are shown in alternating shaded and white quadrants.

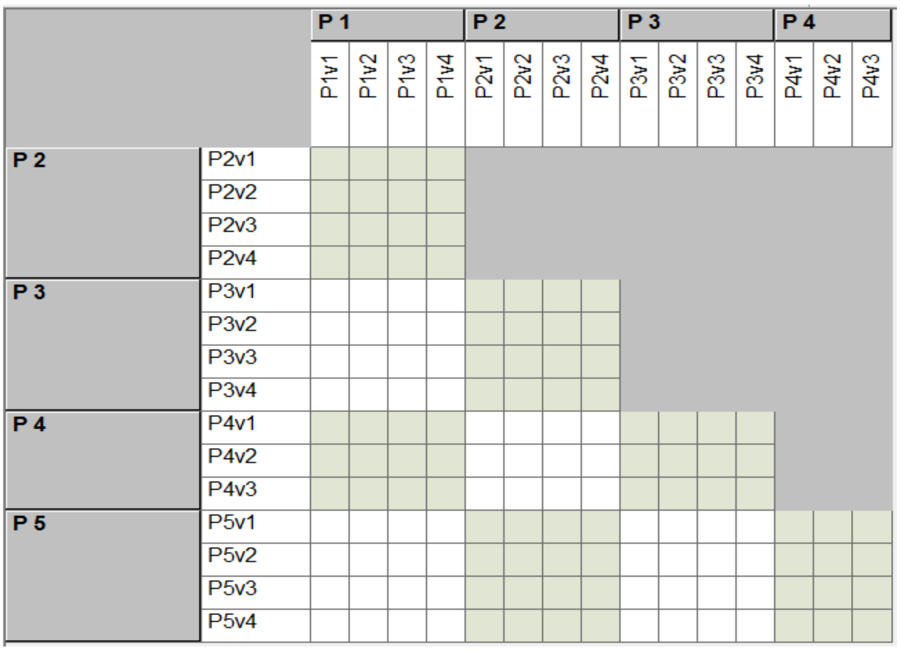

Figure 2: Cross-Consistency Matrix for the morphological field in Figure 1, containing 10 parameter blocks and 144 cross-consistency cells.

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

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

Among other things, this expression represents the number of dyadic (pair-wise) relationships or *connections* between N elements or objects. For instance, it is the number of 2-person interactions possible in a group of N persons. Since in our case the "objects" involved are the dimensions that define a modelling space, then ½N(N-1) is the maximum number of *possible* (formal) connections between those dimensions. How the dimensions of a modelling space are connected is important, since it determines the inference properties of the model. Graph theory is that area of mathematics that treats the pairwise connective relationships between objects (e.g. Figure 5, page 7).

Cross-Consistency relationships between parameter values

If the number of parameters in a morphological model is N and the number of values in the value range of a parameter P_x is v_x, then the total number of dyadic (pairwise) relationships (D_t) between *all parameter values* (and thus the total number of *assessment cells* in the cross-consistency matrix) is:

$$D_t = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} v_i \cdot v_j$$

In the case of Figure 2, in which the five parameters contain 4, 4, 4, 3, 4 values respectively, D_t =144.

To sum up: we have four magnitudes representing the formal properties of the CCA:

N	= number of parameters in the morphological model
½N(N-1)	= number of pair-related parameters (parameter blocks) in the CCM
D_t	= number of paired values (assessment cells) in the CCM
C_t	= number of simple configurations

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

N	½N(N-1)	$\sum_{i=1}^{n-1} \sum_{j=2}^{n} v_i \cdot v_j$	$\prod_{i=1}^{n} vi$
Number of parameters	Number of dyadic relationships between parameters (# parameters blocks)	Number of CCM cells (for v=4) D_t	Number of simple configurations (for v=4) C_t
2	1	16	16
3	3	48	64
4	6	96	256
5	10	160	1024
6	15	240	4096
7	21	336	16384
8	28	448	65536
9	36	576	262144

Table 1: Four formal properties of morphological models (for v=4)

3. Basic Principles of Cross Consistency Assessment

The purpose of the Cross-Consistency Assessment (CCA) is to examine the connective relationships between the parameters of the model's problem space, and distinguish between those relationships that are viable and those that are not. In most morphological fields there will be numerous pairs of values that are mutually incompatible. To the extent that a particular pair of values is incompatible, or indeed is a blatant contradiction, then *all those configurations containing this pair of values would also be internally inconsistent*, and therefore would not represent a viable configuration or possible "solution".

As shown in Table 1, while the number of configurations in a morphological field grows "factorially" with each new parameter, the number of *pairwise relationships between values* grows only in proportion to the quadratic function f(x) = ½x(x-1). This is what makes it possible to employ Cross-Consistency Assessment to reduce a relatively large problem space to a more manageable solution space, without having to examine every configuration in the problem space. For instance, a field of 100,000 formal configurations requires no more than a few hundred pair-wise evaluations in order to create a solution space.

The Cross-Consistency matrix (Figure 2) functions as an accounting table for the CCA process. Essentially, it is relational database but it can also be thought of, and utilised as, a higher level *relational knowledge base* consisting of a set of typologies concerning all of the paired attributes associated with the problem space under consideration.

As was implied in the preceding section, the CCA process actually involves two assessment phases. First, one must determine which of the ½N(N-1) parameter pairs are "connected" and which are not, since only connected parameters need be assessed for internal consistency. The second phase is the CCA proper, which identifies and flags incompatible pairs of values.

In the following discussions we will use a "real life" model to demonstrate the CCA, as this will convey more information than simply using "dummy" parameters. This model is taken from work done for the Swedish National Rescue Services to develop a computer-based instrument to evaluate Rescue Services' preparedness for HazMat (hazardous material) accidents.

The model segment employed here (Figure 3, which is isomorphic to the reference model in Figure 1) represents possible organisational resource levels for Swedish rescue services as concerns preparedness for HazMat accidents. The field has intentionally been kept small in order to serve as a practical evaluation instrument, although even this small field contains 768 potential configurations. As an organisational preparedness model, it was later tested and stressed by connecting it to various HazMat scenarios in order to see how different preparedness resource configurations would cope with different emergency response requirements. One of the main purposes of the model was to ascertain what types of improvements in organisational preparedness would best affect improvements in emergency response. An English language summary of the report of this work is available in Ritchey *et. al.* (2002).

PLANNING/ PLANS	TRAINING AND EDUCATION	PERSONNEL AVAILABLE (for Smoke Diving)	EQUIPMENT AVAILABLE (for specific case)	COMMAND LEVEL
Full preparedness plan	Broad co-op. training	11 or more	Special equipment available	Level 4
Response plan for specific case	Training for specific case	8-10	Only base equipment available	Level 3
Standard routine for general case	Base education + regular training	5-7	Less than base equipment available	Level 2
Only alert plan	Base education only	4 or less		Level 1

Figure 3: Organisational resource field for the HazMat Preparedness Model

A. Determination of parameter connectivity

We begin with *parameter connectivity*, since this needs to be established for a parameter pair before we can start the internal consistency assessment. We say that two parameters in a morphological field are “connected” if they *directly impose constraints on one another*, such that one or more pairs of values in their respective value ranges are incompatible. Put in another way: If we vary the values along the value range of parameter A, and one or more of these values turn out to be incompatible with *any* value of parameter B, then these two parameters are directly connected.

On the other hand, if we find that all of the pairwise values between two parameters are fully compatible and contain no mutual constraints – i.e. that their respective value ranges are effectively independent of one another – then these parameters are not (directly) connected.

The magic word here is “DIRECTLY”. It is often the case that two parameters A and B are *indirectly connected* by way of each being “connected” to a third parameter C. This means that A and B can *indirectly* constrain one another since they are both constrained by C. However, if in addition to this *indirect* connection we also impose a (spurious) *direct* connection between A and B, then we have constrained this relationship twice. Such *double constraints* will risk over-constraining the whole model, with the consequence of choking off otherwise possible configurations. Thus, when examining parameter blocks, one must be pedantically stringent and ask for each block: “Is there really a DIRECT relationship between these two parameters”. (This methodological problem is discussed in more detail below, under “Over-constrained models and truncated solutions”.)

It might seem that the best way to establish parameter connectivity is to simply go through the whole CC-matrix and determine these all at once, i.e. before starting any specific internal consistency assessments. And in certain special cases this is true, for instance if the working group is already well-acquainted with the parameter complex from similar studies; if the model is very large and one needs to make certain assumptions in order to save time; or (and here is a case of special interest) if one has already planned to further develop the model into a Bayesian network, where an internal consistency assessment at this point would be superfluous (see de Waal & Ritchey, 2007).

However, in most cases – and especially in working with open-ended, exploratory problem complexes (which is what GMA is particularly suited for) – it is operationally more practical to determine connectedness *in conjunction with* the internal consistency assessment of each parameter block *per se*. GMA is an *iterative design process*, not a linear step-by-step procedure. At any given point in the process, the meaning of the parameters may shift, values may change, new relationships emerge, and one may need to re-evaluate the whole field. Furthermore, although it is *sometimes* easy to see whether certain parameter pairs are directly connected or not, it is frequently the case that one is not really sure until one actually goes through the internal consistency assessment.

Figure 4 shows the (direct) parameter connections for the HazMat model (blue parameter blocks). Figure 5 shows these connections in the form of a non-directed simple graph.

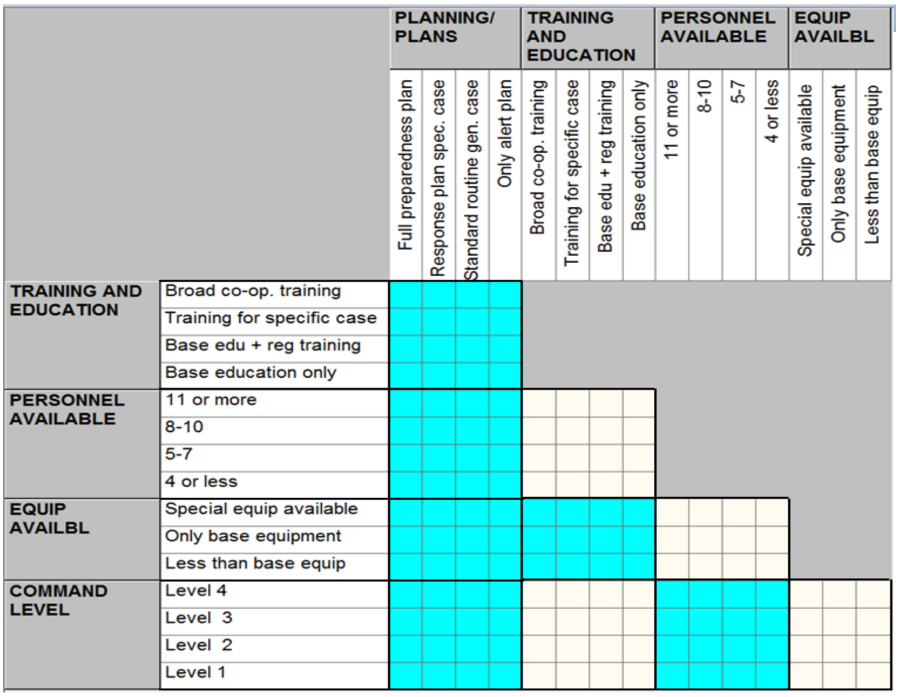

Figure 4: The connected parameter blocks (shaded) in the HazMat model

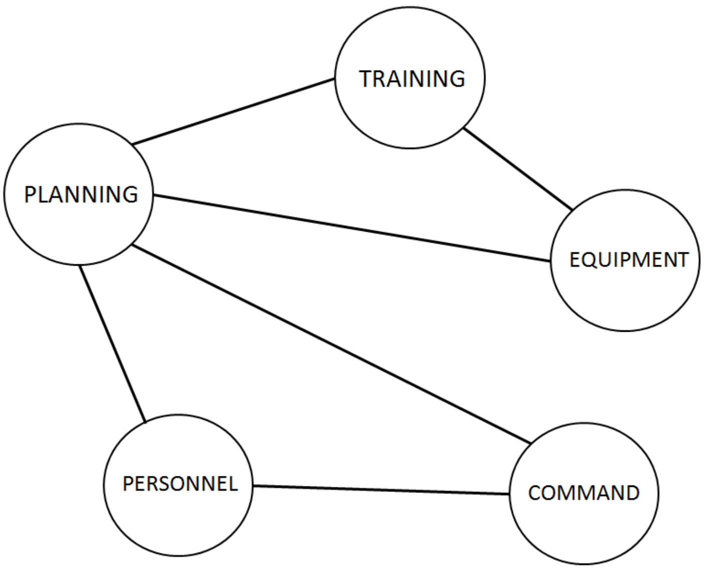

Figure 5: Graph form of the connected parameters of the HazMat model

B. Determination of internal consistency between parameter values

This brings us to the CCA proper: As each pair of values in a (connected) parameter block is examined, a judgement is made as to whether – or to what extent – these are compatible and can coexist. Here there is no reference to causality or direction (as is usual in the case of e.g. a cross-impact analysis), although one can use causal arguments and examples in order to discuss and establish mutual compatibility.

There are two dimensions to these constraints: 1) *Type of constraint*, i.e. what the constraint is about, and 2) *Degree of constraint*, i.e. its strength, level or extent.

1) Types of constraints

There are three *basic types* of constraints involved in a CCA, although there can be any number of specific, user-define constraints (see below). These basic constraints follow the classical distinction between formal, empirical and normative statements:

a. *Formal assessments (logical or analytic contradictions)*
b. *Empirical assessments (empirical incompatibilities)*
c. *Normative assessments (proscriptive constraints)*

a. <u>Formal contradictions</u>

Formal (logical or analytic) contradictions are those which contain no empirical concepts, but are based solely on the nature of the formal relationships between the concepts themselves. For example, in a policy model for the future of the Swedish bomb shelter program in the middle of the 1990's, one of the parameters was termed *Geographical priority* (Figure 6a). It concerned alternative possibilities for concentrating the placement of bomb shelters (e.g. large city centres; smaller cities; industrial complexes etc.). One of the alternative values of this parameter was "Only largest cities". Another parameter was termed *Policy orientation*. One of its alternative values was: "All [people in Sweden] get same shelter quality".

Obviously, these two values do not agree with one another – in fact they are blatant contradictions. Likewise, "All get the same shelter quality" is quite different from "All take the same risk", if one assumes that an adversary would, indeed, make geographical priorities concerning where bombs would fall. But "All take the same risk" is certainly not comparable with "No geographical priority.

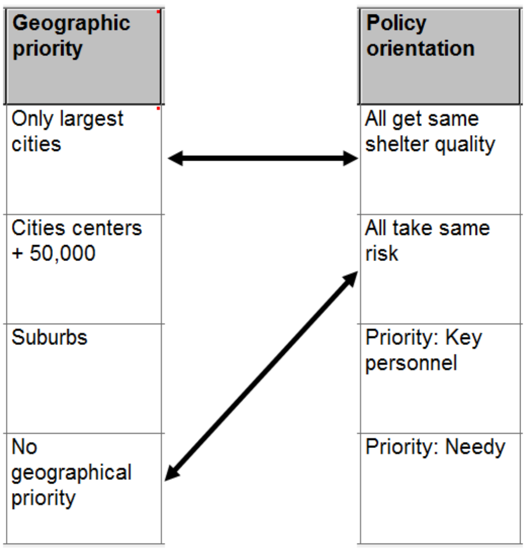

Figure 6a: Two pairs of contradictory values in the Swedish Bomb Shelter model.

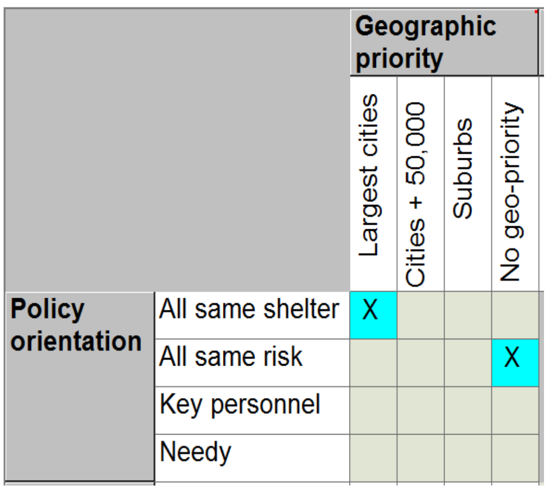

Figure 6b: Contradictory value-pairs marked in CC-matrix

Thus, the two parameters, *Geographic priority* and *Policy orientation* already have built-in (formal) contradictions. (Note that it does not matter that the parameter *Policy orientation* is, in itself, normative in character. The assessment is about the relationship *between* parameter values.) The existence of such formal contradictions in a finished model riles certain individuals. They (correctly) point out that this is a result of *non-orthogonal* parameters being present in the model, and (incorrectly) deem this as inherently bad modelling practice. They feel that such non-orthogonality should have been weeded out already in the parameter formulation phase of the modelling process. However, this misses the point entirely.

Modelling complex social processes and policy spaces (so-called *wicked problems*) involves looking at things from different (stakeholder) positions and perspectives. In the case above, one of the parameters was taken from an economic and technical feasibility study, and the other from a government policy program. In this context, it is exactly by identifying such "non-orthogonal" ranges of positions that we reveal and better understand the complex sets of conflicting issues involved in social planning processes. *Enslavement to orthogonality* – feeling that one must do away with such non-orthogonal parameters at the outset – undermines the whole point of such an enquiry. By definition, "wicked problems" lack internal consistency. This is what (among other things) makes them *wicked*.

Thus *formal contradictions* are of great interest from the point of view of revealing inconsistencies/incompatibilities in policy positions and stakeholder perspectives. However, they usually make up only a small portion of the constraints found in morphological models. The main types of constraints involve *empirical* and *normative* relationships.

b. Empirical incompatibilities

Empirical incompatibilities are based upon relationships that we deem impossible or highly improbable due to our acquired knowledge and experience of the world, e.g. the "laws of nature", the (present) state of technology or the consequences of perceived "limited resources". An example of empirical inconsistency comes from a study of Multi-Hazard Disaster Risk Reduction Strategies done at the Earthquake Disaster Reduction Center (EDM) in Kobe, Japan (Ritchey, 2006b). One of the parameters dealt with different *Types of hazards*, another with different *Types of risk reduction strategies* – from actively preventing the very occurrence of the hazard type itself, to reduction of is consequences, to only risk transfer. Obviously, not all Risk Reduction Strategies are applicable to all Hazards – at least not yet. For instance, earthquakes cannot (yet) be prevented, but we can reduce their consequences through proper building techniques and codes.

Figure 7a**:** (below) shows three hazard types which are not – at the present time – susceptible to physical *prevention*, or even to reduced severity as such (marked with "X"). The "?-keys" flag relationships that lie just outside the boundaries of these incompatible relationships and which should be discussed in order to better establish where this boundary is.

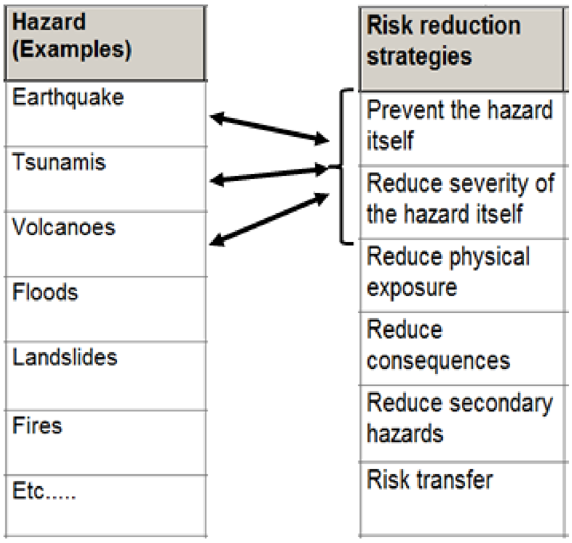

Figure 7a: Incompatible empirical relationships.

	Risk reduction strategies						
		Prevent the hazard	Reduce severity	Reduce exposure	Reduce consequences	Reduce secondary	Risk transfer
Hazard (Examples)	Earthquake	X	X	?	-	-	-
	Tsunamis	X	X	?	-	-	-
	Volcanoes	X	X	?	-	-	-
	Floods	?	-	-	-	-	-
	Landslides	?	-	-	-	-	-
	Fires	?	-	-	-	-	-

Figure 7b: As represented in the Cross-Consistency matrix.

c. Normative constraints

While *empirical* assessments are based on descriptive statements and concern what we consider as being *possible* or not, *normative* assessments are prescriptive (or proscriptive) and concern how we feel that things *ought* to be, i.e. what we deem as being *desirable* or not. Strategy and policy modelling have strong normative aspects.

There are many different ways to describe and categorize the "normative", but for the purposes of this paper we need to distinguish between two different types of normative assessments. We shall term these the *normative-practical* and *normative-ethical*.

Normative-practical assessments are about "good practice" from a strategic, operational or functional point of view. These are prescriptive (or proscriptive) assessments concerning efficient ways for achieving objectives, as well as the objectives themselves. As such, normative-practical assessments contain an empirical aspect, i.e. they are based on our experience and notions of what works. However, it is not about what is possible and not possible (this is taken care of with "empirical assessments"), but what is deemed as more or less reasonable, functional and/or effective.

Normative-ethical assessments, on the other hand, are value-based judgments concerning ethical and ideological issues, e.g. how we ought to treat our fellow human beings. As Socrates put it, it is about the *condition of our souls*. It is often the case that normative-practical considerations come into conflict with normative-ethical ones. This is why the distinction is so important for social science and policy modelling. The distinction turns up constantly in the CCAs of most "wicked problems" – which are policy-based problems.

Normative constrains are no less important than logical and empirical constraints, but we must not confuse these two domains. We neither want quasi-logical and/or spurious empirical arguments to mask legitimate ethical concerns; nor do we want ideological based arguments to masquerade as grounded evidence. Importantly, normative constraints are also often associated with institutional decision points (see below).

An example of *normative-practical* constraints is shown in Figure 8, concerning the relationship between “training and education”, and “equipment available” in the HazMat organisational model. The fire chiefs and engineers in the working groups pointed out that it is fully possible to make specialised equipment available to virtually all rescue services, but that it is bad policy to supply these expensive and limited recourses unless it is accompanied by proper training. Although this particular example might seem trivial, it turned out that this and similar issues had caused problems in the past, and were not considered trivial at all. A similar problem is involved in the relationship between “broad co-operative training” and “less than basic-level equipment available”.

GMA works with ordinal (scaled) and non-ordinal category variables (which will be discussed in more detail in the forthcoming paper “Principles of Parameter Formulations in GMA”). Here we are working with two *scaled* category variables. In such cases (as in Figure 8b) we find that constraints tend to cluster in the corners of the opposite extremes of the variables, leaving an open “main sequence” of possibilities running along the other diagonal (i.e. the assessment cells with the hyphens).

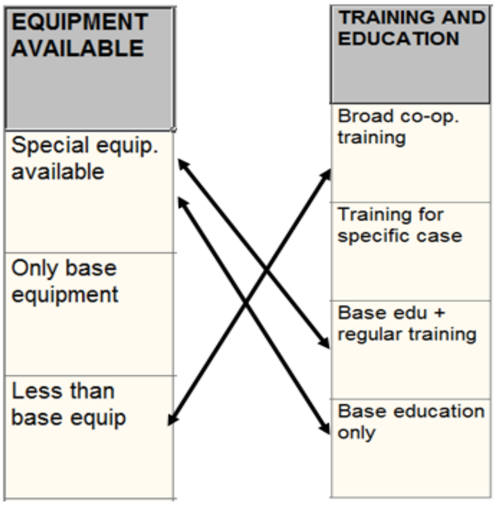

Figure 8a: Normative-practical constraints along two scaled variables

		EQUIPMT AVAILABL		
		Special equip.	Only base	Less than base
TRAINING AND EDUCATION	Broad co-op. training	-	-	X
	Training for specific	-	-	-
	Base edu + training	X	-	-
	Base education only	X	-	-

Figure 8b: Constrained value pairs (X) clustered in opposite corners.

An example of *normative-ethical* constraints is given in Figure 9. In a series of workshops carried out for the Ministry of Education for an Asian country, we modelled the concept of “assessment”, i.e. the process and purpose of evaluating student performance in the educational system. The primary parameters used for this modelling were:

- What can be assessed (at the student level)
- The immediate purpose of assessment (for the school)
- The broader societal purpose and role of assessment
- Different methods of assessment
- Primary drivers or stakeholders for assessment
- Unintended consequences of assessment

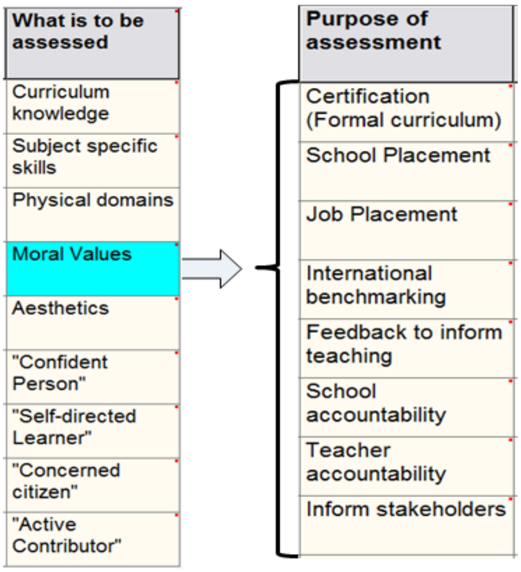

Figure 9a: The question of moral values in student assessment.

		Purpose of assessment							
		Certification	School Placement	Job Placement	Internat. benchmarking	Feedback	School accountability	Teacher accountability	Inform stakeholders
What to be assessed	Curriculum knowledge								
	Subject specific skills								
	Physical domains								
	Moral Values	?	?	?	?	?	?	?	?
	Aesthetics								
	"Confident Person"								
	"Self-directed Learner"								
	"Concerned citizen"								
	"Active Contributor"								

Figure 9b: For what purpose would one assess students' moral values

One of the values of the parameter "What can be assessed" is *moral values* (of the student). Now it may be questioned as to whether "moral values" should be assessed at all, but this is not the immediate problem. During the parameter formulation phase, we recommend that all possible values of a parameter be identified, even those of (seemingly) dubious character. Banning concepts at this stage is counter-productive. The character of such questionable parameter values will be revealed during the CCA. If they remain questionable, then this is something that the model should show, i.e. "this particular value of this parameter has no reasonable or moral application". Leaving this information out of the model would simply be hiding an important modelling result – akin to suppressing negative results in medicine or pharmacology. The immediate problem here is this value's relationship to other parameters, as seen in Figure 9. Which of the "Purposes of assessment" would you accept on ethical grounds to judge your students: all of them; none of them; some of them? Which ones?

To sum up: While most morphological models contain a combination of empirical and normative issues, some are almost totally empirical, while others are almost totally normative. It depends on the nature of the subject being addressed, and how parameters are formulated.

d. <u>User-defined constraints</u>

Beyond the three basic categories of constraints defined above, there is the possibility of employing more *specific, user-defined constraints*. These are used in order to "flag" certain conditional relationships and issues of interest in the modelling context. Examples are:

- This is possible, but unrealistically expensive
- This is possible, but too risky for our personnel under normal circumstances
- This is a "wild card" (e.g. a possible possibility via new, emerging technology)
- This is possible, but it requires a policy decision from higher-ups (*decision point*)

This last "flag" is an interesting and important one. It will be discussed below under ""Flagging decision points".

2) Degree of constraints

So much for *types* of constraints. What we mean by the "degree" of a constraint concerns to what extent the constraint constrains: completely, partially, conditionally, etc. Both Zwicky (1969), the founder of general morphology, and Rhyne (1981), who continued to develop GMA post-Zwicky, employed only two degrees of constraints: either a pairwise relationship was possible, or it was not. Nor did they make any distinction between "Types of Constraints". This was fully understandable at the time: they were working with GMA by hand, which is a major challenge even without having to complicate things with "types" and "degrees". However, with the advent of advanced computer support for GMA in the mid-1990s, these added distinctions could be applied, which opened up entirely new possibilities.

Today we can define any number of degrees or levels of constraints, although one must do this with good judgement. The problem here is *false resolution*. The degree of resolution attributable to a pair-wise assessment, and to a model's variables in general, depends on the nature of the problem being addressed, and the resolution and certainty of the knowledge available. It is not justified to create a model of significantly higher variable resolution than is the knowledge available concerning the modelling object. There is no use applying nanometre precision when you are working with a sledge hammer. Fortunately, this problem shows up in the CCA and can be treated (see "Over and Under Resolution" in Section 5. Special topics).

Normally, for the types of ("wicked") problems that we treat with GMA, three levels of constraints will suffice (plus a few user-defined "flags"). We use the following three basic *assessment keys*[*]

— = Possible; what one would expect; good fit

K = Possible; but not optimal; on the boundary

X = Impossible

Each of these can, in turn, be "typed", i.e. as formal, empirical or normative (Table 2).

Type→ Degree	Formal	Empirical	Normative
— (hyphen)	Possible	Quite alright; good fit; or optimal	No problem, even desirable
K	Possible	Not-impossible; not-optimal, unlikely or far-fetched	Debatable; problematic
X	Impossible (formal contradiction)	Impossible or not viable; e.g. goes against laws of nature, etc.	Unacceptable on functional or ethical/moral grounds

Table 2: Main categories of constraints: degrees x types.

[*] The symbols for these "assessment keys" were chosen, under time stress, during the original programming phase of the software in 1995. They stuck.

4. Facilitating the CCA process

Again, (and one cannot harp enough about this) the GMA process is not a linear, step-by-step procedure, but involves a continual process of re-adjustment and re-evaluation; facilitated cycles of enlightenment and confusion, enthusiasm and frustration. The CCA itself is a good example of this: It is most often the case that the first attempt to carry out the CCA quickly reveals that certain concepts in the initial morphological field are too vague or equivocal, too detailed or too coarse, and need to be adjusted or perhaps completely re-worked – sometimes in several iterative steps. Indeed, we consider the initial attempt at a CCA to be part of the overall design process for the *main morphological field* itself. This is why we no-jokingly call the CCA a "garbage detector".

It is crucial that the GMA process as a whole be facilitated by a professional, totally impartial, "outside" facilitator who has *no stake* in the problem complex being addressed. For the CCA phase, the facilitator's task is to systematically ask the working group questions about the nature of the relationships between parameter values. It is of the utmost importance that these "questions" be *framed* carefully and precisely, and discussed with the group. Is this the *right* question? Does the question make *sense*? Are there other ways to formulate this question? In many cases the question makes perfect sense and it will seem silly to have to make such a production of the matter. However, one can almost never be certain of this beforehand. When dealing with more complicated concepts, the relationships between values can be deceptive and ambiguous; sometimes seemingly incomprehensible until they are discussed and framed properly.

Furthermore, different participants in the working group often come from quite different backgrounds and have radically different ideas about what certain of the modelled concepts mean. You may have to rename, reformulate or completely redefine specific concepts, or even whole parameters. This is a natural part of the *iterative design process* embodied in GMA. Rush through this process at your own (and your client's) risk.

Operationally, the CCA begins by selecting the first two values in the first two parameters (Figure 10a), which corresponds to the first pairwise assessment in the first parameter block in the CC-matrix, shown in the dark blue (or darker shaded) assessment cell in Figure 10b.

PLANNING/ PLANS	TRAINING AND EDUCATION	PERSONNEL AVAILABLE (for Smoke Diving)	EQUIPMENT AVAILABLE (for specific case)	COMMAND LEVEL
Full preparedness plan	Broad co-op. training	11 or more	Special equipment available	Level 4
Response plan for specific case	Training for specific case	8-10	Only base equipment available	Level 3
Standard routine for general case	Base education + regular training	5-7	Less than base available	Level 2
Only alert plan	Base education only	4 or less		Level 1

Figure 10a: Starting point for CCA – the first two cells of the first two parameters.

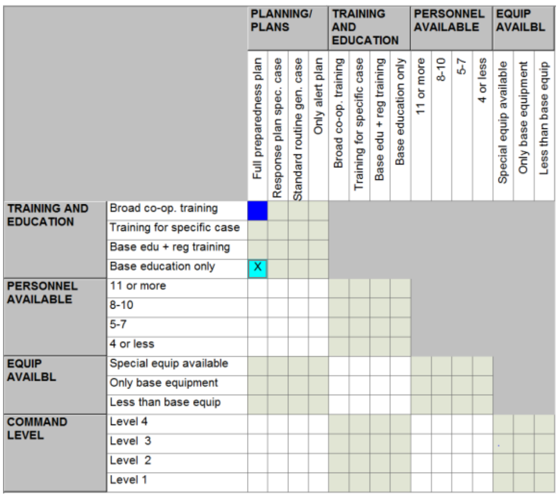

Figure 10b: Corresponding pairwise cell (dark blue) in Cross-Consistency matrix

Since we recommend examining the question of parameter connectedness *at the beginning of each internal consistency assessment for each parameter block*, we start off by asking the following question:

> "Is there a DIRECT connection between the "Level of Hazmat planning" and the "Level of education and training for Hazmat response"?

If the answer is "no", then we leave this block "blank" and go on to the next parameter block (in the case of Figure 10b, the one under it).

If the answer is "yes" (which, in this case, it is), then we systematically and pedantically go though each cell in the block, and ask if these two particular parameter values can/should co-exist? In the case at hand (for the initial dark blue cell in Figure 10b) the question would be *framed* something like this:

> If a Rescue Service has a "Full preparedness plan", is this compatible with it having a "Broad co-operative training" program?

In this case, the answer is definitely "yes" – not only are they compatible, but are an *optimal pair*. We give this pair-wise relationship a "—" (hyphen) and consider whether this is an empirical-descriptive or an empirical-prescriptive issue.

In contrast to this, when we eventually work our way down to the bottom of the column (the light blue, X-marked cell in Figure 10b), we ask the question:

> If a Rescue Service has a "Full preparedness plan", is this compatible with it having "Base education only"?

The answer to this question is "no". We give the cell an "X" and discuss if this is a descriptive or normative judgement.

		PLANNING/ PLANS				TRAINING AND EDUCATION				PERSONNEL AVAILABLE				EQUIP AVAILBL		
		Full preparedness plan	Response plan spec. case	Standard routine gen. case	Only alert plan	Broad co-op. training	Training for specific case	Base edu + reg training	Base education only	11 or more	8-10	5-7	4 or less	Special equip available	Only base equipment	Less than base equip
TRAINING AND EDUCATION	Broad co-op. training	-	-	X	X											
	Training for specific case	K	-	-	X											
	Base edu + reg training	X	K	-	-											
	Base education only	X	X	-	-											
PERSONNEL AVAILABLE	11 or more	-	-	X	X	-	-	-	-							
	8-10	-	-	-	X	-	-	-	-							
	5-7	-	-	-	-	-	-	-	-							
	4 or less	-	-	-	-	-	-	-	-							
EQUIP AVAILBL	Special equip available	-	-	X	X	-	-	X	X	-	-	-	-			
	Only base equipment	-	-	-	-	-	-	-	-	-	-	-	-			
	Less than base equip	X	X	-	-	-	-	-	-	-	-	-	-			
COMMAND LEVEL	Level 4	-	-	-	-	-	-	-	-	-	K	X	X	-	-	-
	Level 3	K	-	-	-	-	-	-	-	-	-	K	X	-	-	-
	Level 2	X	K	-	-	-	-	-	-	X	-	-	K	-	-	-
	Level 1	X	X	-	-	-	-	-	-	X	K	-	-	-	-	-

Figure 11: Assessed HazMat preparedness model.

Figure 11 shows the finished CCA for the HazMat model. Note how the constrained (X) cells tend to gather in corners of the connected parameter blocks. This is typical for models in which many or all of the parameters are scaled, and where pairwise extremes in one diagonal constrain each other. For the model as a whole, these constraints gather in corners of the higher dimensional hyper cube.

5. Special topics

Documentation

The CCA *must be documented during the CCA process itself*. Where not *totally obvious*, the reasons and motivations for each assessment must be recorded. Where relevant, examples should also be given. This is because these "reasons" will easily be forgotten or confused if they are not preserved immediately. When presenting the models for clients and other stakeholders, one must have instant access to this information. Questions will concern both X-constrained cells: "Why do you think that this particular pair relationship is impossible or implausible?", and "open" (hyphened) cells: "Do you really think that this is possible? Give us an example." If you can't answer these questions confidently, you're dead meat.

Over-constrained models and truncated solution spaces

The degree to which a model is constrained is measured by the ratio of the number of simple configurations in the *solution space* to the number of simple configurations in the *total problem space*. This is called the *solution space quotient*. The size of this ratio depends on a combination of *how many* X-assessments appear in the CC-matrix and their *distribution*. A model is hyper-constrained when this ratio is very low, and there are very few solutions to a relatively large problem space. Likewise, a model is hyper-coherent when the number of solutions is nearly as large as the problem space itself. For most morphological fields the *solution space quotient* lies somewhere between 1-10%.

There is nothing necessarily wrong with models that are hyper-constrained or hyper-coherent. These conditions are expressions of the nature of the problem being modelled. For instance, scenario models concerning long-term futures are often hyper-coherent and have large solutions spaces – mirroring the fact that it is difficult to confidently exclude many possible empirical developments in the long-term.

However, when a model is spuriously *over-constrained,* it often means that it has been over-connected, sometimes representing a *completely connected* graph. This is when all of the variables have been *directly connected* to one another, which is unusual in a morphological model. However, when one is new to the CCA technique, it is easy to over-constrain by trying to find incompatibilities in every parameter block. Our mind tends to jump ahead and ascribe *direct relationships* between parameters when these are actually indirect. One must be stringent and ask for each block: "Is there really a DIRECT relationship between these two parameters".

Choked values ranges and Off-Switches

Sometimes you may find that *none of the values* in the value range of parameter B is compatible with a particular value in parameter A. Thus one marks all of the pairwise assessment with "X" (as in Figure 12, below). This will have the effect of choking off the model and rendering inaccessible other possible (legitimate) solutions which are dependent on this value range. For this reason, we introduced a security measure into the software that demands that all value ranges be "exhaustive". This does not mean that one needs to positively list every possible case in the conceptual universe for every variable. It means that if you come across a value range that does not offer you at least one "-" or "K" when it is being assessed, then you must extend that value range with an "Off-Switch". That is, you make the value range "exhaustive" by adding to it an extra value such as "None of the above" or "Not relevant". This also gives us the possibility of asking the model to show all of the solutions which *do not include* any of the (other) values in the designated parameter – on occasion a very useful question.

-	-	-	X
-	-	-	X
-	-	-	X
-	-	-	X

X	X	X	X
-	-	-	-
-	-	-	-
-	-	-	-

Figure 12: Forbidden assessments: There must be at least one compatible value for every value range.

Over- and Under-Resolution

During the parameter formulation phase of the GMA there will often be disagreements among the workshop participants as to how many values are needed in a particular parameter – i.e. the parameter's *value resolution*. For example, someone may think that "Large", "Medium" and "Small" is quite sufficient for a particular rank-order variable, while another may think that this is too coarse grained and that *added resolution* is required – e.g. "Very large", and/or "Very small" – in order to correctly represent the problem. In general, it is better to provisionally accept the *more extensive* value range, and explain to the group that the matter will be resolved when one comes to the CCA phase.

Usually, if the value range is too detailed, then adjacent values in a parameter will be assessed exactly the same for the whole model – i.e. the resolution is too high and these two values are too close to be distinguishable. Since they are always assessed the same, they will have the same affect on the model, and they can be fused. If, on the other hand, one finds that a single particular value seems to be too broad and doesn't offer enough resolution to distinguish between important differences in other parameters, then it needs to be split into two or more levels. Such adjustments in parameter resolution are part and parcel with the (iterative) CCA process.

Flagging decision points

Especially in working with strategy and organisational management models, one will often find pairwise assessments that are empirically possible and ethically unobjectionable, but which require a *decision* on organisational policy grounds. E.g. "Do we want to continue with this product line", "Should more research be put into this area" or "Do we need to down-size"? Often, such decisions cannot be made at the level of the group doing the strategic modelling, but must be referred to higher-level management (who, by their very nature, have not been allowed to take part in the modelling sessions since they tend to dominate and skew the proceedings – but this is an issue for another article). These "decision point" cells can be flagged and later presented to those organisational higher-ups whose job it is to make just such difficult strategic decisions. Indeed, the prospect of confronting top management with truly "wicked" decision points usually results in much merriment among the workshop participants.

Finally: There are any number of other specific issues and aspects, tricks of trade and pitfalls involved in the process of carrying out a CCA, many of which simply must be learned "on-the-job". However, I hope that this article has served as a useful primer for those who wish to learn the art of CCA.

6. Glossary

Cross Consistency Assessment - CCA: Pertains to the process by which the *parameter values* in the *morphological field* are compared with one another, pair-wise, in the manner of a cross-impact matrix. As each pair of values is examined, a judgement is made as to whether - or to what extent - the pair can coexist, i.e. represent a consistent relationship.

Connectivity (Linkage): Concerns how parameters in a Morphological Field are connected or linked, i.e. which parameters constrain each other, and which do not.

Consistency: Degree of compatibility between the *values* of different *parameters* in a morphological field.

Configuration: At least one value displayed from each of the parameters in a morphological model.

Hyper-Coherent: When the degree of compatibility or internal consistency between parameters in a morphological model is very high, and many possible solutions or outcomes are obtained.

Hyper-Constrained: When the degree of compatibility or internal consistency between parameters in a morphological model is very low, and few possible solutions or outcomes are obtained.

Morphological Field: The field of constructed dimensions or parameters which is the basis for a morphological model.

Morphological Model: A morphological field with its parameters assessed and linked through a Cross-Consistency Assessment (CCA).

Parameter: One of a set of measurable factors that defines a system and determines its behaviour, and which can be varied in an experiment.

Parameter space: A set of mutually linked parameters making up the Morphological Field.

Parameter Value range: The different values a parameter can take (see Diagram 1)

Problem space: The totality of the possible configurations obtained in a Morphological Field (see Solution space).

Simple configuration: One and only one value displayed from each of the parameters in a morphological model.

Solution Space: The subset of all of the configurations in a morphological model which fulfil the requirement of being internally consistent, and thus being a possible solution.

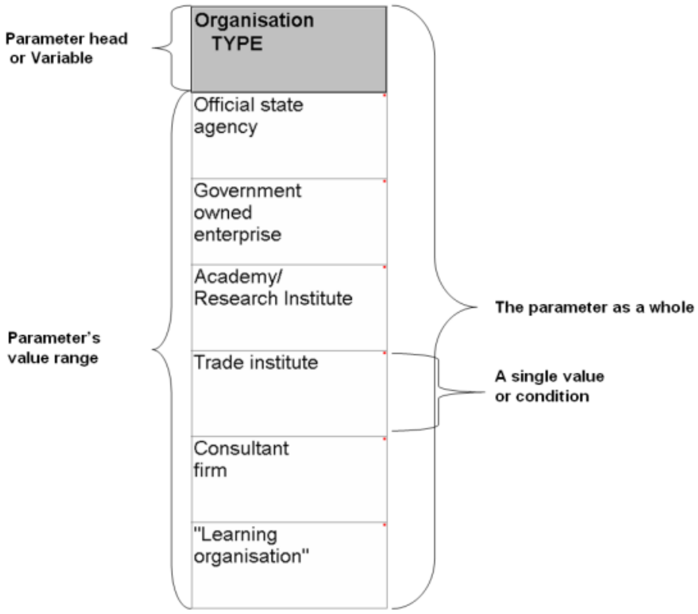

Figure 13: Parameter terminology

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