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Large-scale scenarios as ‘boundary conditions’: A cross-impact balance simulated annealing (CIBSA) approach

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Abstract

There is increasing interest in cross-scale scenario development, driven in part by developments in climate scenarios. Climate mitigation and adaptation studies have long emphasized the link between global change and local action, and recent climate community scenarios have been developed with cross-scale application in mind. Conceptually, global scenarios have been proposed as ‘boundary conditions’ on regional and local scenarios. However, while the concept is compelling, to date we have found only one formal proposal (by Schweizer and Kurniawan) of what it might mean from a scenario development perspective. That proposal used cross-impact balances (CIB), which offer a promising route to formalization of cross-scale scenario analysis. In this paper we also apply CIB, but allow for weak, rather than zero, cross-scale interactions. We formalize the concept of weak interactions by extending CIB analysis to allow for metastable states, which are stable under small disturbances. We propose an algorithm for identifying metastable states and for combining states that become connected when small disturbances are present. Arguing that large-scale scenarios can be applied as boundary conditions when they are metastable under the influence of processes at smaller scales, we demonstrate how a simplified CIB can replace a full multi-scale CIB when a metastable scenario kernel is adopted at large scale.

Keywords: CIB; cross-scale; boundary condition; metastability; simulated annealing

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Introduction

In any scenario exercise, a boundary must be drawn around the system under study. Yet, all systems of interest in scenario studies are open to their environment, because they are far from equilibrium – they are living, not dead – and each such system must maintain a flow of energy and materials across its borders (Feistel and Ebeling, 2011). Any processes outside that system become external 'driving forces' that impinge upon the system of interest but are not affected by it. A chronic concern is whether the boundary has been well drawn, and if analytic separation of the sub-system from the whole system will lead to poorly-specified scenarios and problematic policies. This difficulty is by no means unique to scenarios, but Futures Studies is a particularly appropriate area in which to examine it because of the emphasis on openness, uncertainty and surprise (Bell, 1997).

Recognition that all borders are at least partly porous has driven interest in explicitly multi-scale scenario analysis, with examples from integrated assessment (Kok et al., 2006), sector-wide strategic planning (Goodier et al., 2010), smallholder silviculture (Dermawan et al., 2013) and ecosystems embedded within socioeconomic systems (Pahl-Wostl, 2002). Preparation of a new climate scenario framework (O'Neill et al., 2014, 2017) has brought the need for multi-scale techniques to the fore in order to better meet the needs of the impacts, adaptation and vulnerability (IAV) community (Moss et al., 2010; van Ruijven et al., 2014). One prominent strategy, which is an extension of the analytical separation of systems at different scales, is to apply scenarios developed at larger scale as 'boundary conditions' for scenarios generated at smaller scale (Absar and Preston, 2015; Kok et al., 2006; Nilsson et al., 2017; Wilbanks and Ebi, 2014). Yet, as noted by Schweizer and Kurniawan (2016), these approaches have so far used 'soft' methods, while their paper represents the first published attempt at a formal method.

In this paper we develop and apply a methodology for linking scenarios across scales. Following Schweizer and Kurniawan (2016), we use cross-impact balance (CIB) analysis (Weimer-Jehle, 2006) to systematically approach the problem of developing scenarios for hierarchies of systems. CIB is a semi-quantitative method in which scores are assigned to pairwise influences between the states of 'descriptors'. Those scores are then used to compute the influence of each possible state of the system under study on every other state. Schweizer and Kurniawan treated the case of sparse cross-impact matrices in which many descriptors have negligible interactions. Efficient methods allow them to solve the sparse system in a reasonable time. The innovations we introduce are: first, to provide a theoretical justification for hierarchical structures in multi-scale scenarios; second, to formally aggregate a cross-impact sub-matrix; and third, reduce computation time for dense matrices by aggregating at the highest level. The aggregate analysis then provides a formal justification for a boundary condition approach.

We first construct a general analysis in which a full set of descriptors is available at all scales. We then note that in many situations the larger-scale environment can be collapsed to a single descriptor, yielding a reduced analysis that is considerably simpler than the full analysis. The essential strategy is to formalize the process of applying large-scale scenarios as 'boundary conditions' on scenarios at smaller scale. We find a criterion for when such an approach is appropriate by applying formal results for CIB analysis (Weimer-Jehle, 2009). We extend the CIB methodology by considering fluctuations at the smaller scale that can potentially destabilize scenarios at the larger scale, and argue that the large-scale scenario kernel (that is, the set of scenarios as defined by their descriptor states) should be stable against such fluctuations. We formalize this idea for CIB and introduce an algorithm to identify such 'metastable' scenarios, which we call CIB simulated annealing (CIBSA). While the notion of metastability applies to any CIB analysis, we use the idea specifically for multi-scale systems.Note that while we use the language of spatial scale and speak of smaller-scale sub-systems embedded in larger-scale systems, the approach developed here can be applied to any situation in which sub-systems are embedded within a system, even where spatially defined boundary is not the salient feature. For example, scenarios of a corporation or sector embedded in the world economy, scenarios of the carbon cycle embedded in the larger socio-geophysical system, or population scenarios embedded in the larger societal system. Thus, the method can be applied whenever some relevant dimensions constitute the degrees of freedom for scenario exploration, while additional dimensions can be treated as constraints, boundary conditions, or exogenous drivers. For concreteness, our discussion of multi-level systems assumes that they can be meaningfully divided into three parts: a *planning entity*, a *transactional environment*, and a *contextual environment*. In this we follow van der Heijden (2005), who in turn was following Emery and Trist (1965).

Cross-impact balance analysis

The cross-impact balance (CIB) approach assumes that the system in which an organization is embedded can be defined by a finite set of 'descriptors', which can each take on a finite number of 'states'. This is equivalent to saying that the system can be represented by a morphological field (Ritchey, 2018, 2011, 2006). A morphological field is a convenient formulation for scenario exercises because it conforms to an important output – a set of driving forces and a finite set of possible future states – from an intuitive logics exercise. Intuitive logics is arguably the most popular approach to developing scenarios (Bradfield et al., 2005; van der Heijden, 2005).

Morphological fields offer a very general representation of finite-state systems, and Weimer-Jehle (2009 property XXIV) has shown that the dynamic processes of any finite-state system can be cast in terms of CIB. In reality, we live in a world that combines continuous and discrete processes, and continuous processes have infinite numbers of possible states. Yet, it is not always feasible or desirable to represent those processes in detail. Morphological analysis and CIB invite qualitative descriptions of dynamical systems, thereby capturing some features of reality (processes that are hard to quantify) while simplifying others (continuous processes with infinite states).

We use the notation of Weimer-Jehle (2009), in which a 'scenario' is a set of descriptor states, one for each descriptor. When written on its own, a scenario is indicated by an underlined letter, but is not underlined when writing the 'inner product', or total impact of one scenario on another. For example, a scenario $\underline{u}$ has descriptor states u_i, where i runs from 1 to N, with N the number of descriptors. The inner product of $\underline{u}$ with another scenario $\underline{v}$, i.e. the sum of the scores for the impacts of scenario $\underline{u}$ on scenario $\underline{v}$, is computed as

$$\langle u \,|\, v \rangle \equiv \sum_{i,j=1}^{N} C_{ij}(u_i, v_j). \tag{1}$$

In this expression, each $C_{ij}(u_i,v_j)$ is a 'judgement cell', or cross-impact score for the influence of descriptor i on descriptor j when their respective states are u_i and v_j. It indicates the degree to which descriptor i in state u promotes or diminishes descriptor j in state v. The impact of scenario $\underline{u}$ on scenario $\underline{v}$ thus reflects the degree to which $\underline{u}$ reinforces or undermines scenario $\underline{v}$. The inner product of a scenario with itself is a measure of internal consistency.

The partial sums across the index i in equation (1) are the impact scores $\theta_{jr}(\underline{u})$, with $r = v_j$, where

$$\theta_{jr}(\underline{u}) \equiv \sum_{i=1}^{N} C_{ij}(u_i, r). \tag{2}$$

In CIB analysis, descriptor-specific consistency is the difference between the impact score for the chosen state of that descriptor and the highest impact score among the other possible states of that descriptor, while scenario consistency is the minimum of the consistency scores across its descriptors. A scenario with a negative consistency score is inconsistent, while a scenario with a positive or zero consistency score is consistent.

Consistent scenarios are the endpoints of a process known as ‘CIB succession’ (Weimer-Jehle, 2009, p. 4). In CIB succession, a given inconsistent scenario is adjusted toward toward greater consistency in a stepwise fashion by applying a succession operator *S*, which is defined by the cross-impacts matrix *C* and a specific succession process. Many succession operators can be defined, but they are all characterized by processes that lead to progressively more consistent scenarios, and it has been shown that they all lead to the same endpoint scenarios (or to cycles) (Weimer-Jehle, 2009, p. 4). An example of a succession operator often used in CIB is ‘global succession adjustment’, in which all inconsistent descriptors are adjusted to the state of highest impact score. Another example is ‘incremental global succession adjustment’, in which all inconsistent descriptors are adjusted toward the state of highest impact score, but only by adjusting to a neighboring state.

CIB succession can be thought of as analogous to a dynamic process, in which inconsistencies cause ‘forces’ that drive the system toward consistent endpoints. Those endpoints are ‘attractors’ and all scenarios that lead to a particular consistent scenario under succession constitute its ‘basin of attraction’. This dynamic interpretation of CIB will play an important role in the subsequent discussion.

Cross-impact balance simulated annealing

CIB consistency provides a formal definition of a consistent scenario kernel (Bishop et al., 2007) K_0 as the set of scenarios $\underline{u}$ satisfying (Weimer-Jehle, 2009, p. 3)

$$K_0 = \left\{ \underline{u} : \theta_{ir}(\underline{u}) \geq \theta_{ir'}(\underline{u}), \quad \forall i \in [1, N], r' \neq r = u_i \right\}. \tag{3}$$

By summing over the *j* index and using the definition of the inner product in equation (1), we find that each consistent scenario $\underline{u}$ in K_0 satisfies[1]

$$\langle u | u \rangle \geq \langle u | v \rangle, \quad \forall \underline{v} \neq \underline{u}. \tag{4}$$

FLUCTUATIONS AND BUBBLES

As noted above, in CIB each element in the scenario kernel is the unique endpoint of a succession process[2]. That process is deterministic – given a starting point in the basin of attraction of a consistent scenario, succession will lead to it. This determinism is questionable if the larger environment varies in ways that are difficult to anticipate (Emery and Trist, 1965) but that have non-negligible effects. In this case the contextual system is driven by what seem, to the local actors, to be random fluctuations. We can picture the contextual system as analogous to a pot of water on a lit stove before the water boils. As it comes close to boiling, small bubbles form and either grow or collapse. By analogy, in the contextual system, isolated areas may be characterized by a different scenario than the bulk.

Using the CIB formalism, suppose that the external environment is initially in the consistent scenario $\underline{u}$. For any other consistent scenario $\underline{v}$, we know from the consistency condition in equation (4), that

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[1] The converse is also true: if the following inequality holds for every scenario $\underline{v}$, then scenario $\underline{u}$ is consistent (Weimer-Jehle, 2009 property XV). Thus, inequality (4) is an alternative consistency condition.

[2] Cycles are excluded from the kernel.

$$\langle u|u\rangle \geq \langle u|v\rangle \quad \text{and} \quad \langle v|v\rangle \geq \langle v|u\rangle. \tag{5}$$

Suppose further that for a particular choice of $\underline{v}$ the first of these happens to be an equality, while the second is an inequality,

$$\langle u|u\rangle = \langle u|v\rangle \quad \text{and} \quad \langle v|v\rangle > \langle v|u\rangle. \tag{6}$$

Following the analogy to the water on the stove, we can ask what happens if a 'bubble' like scenario $\underline{v}$ forms in a contextual environment characterized externally by scenario $\underline{u}$. From the first expression in (6), which is an equality, $\underline{u}$ is just as reinforcing for $\underline{v}$ as it is for itself. That means there are no 'forces' to make the bubble shrink. However, from the second expression in (6), an inequality, there are forces to make it grow, because scenario $\underline{v}$ is more strongly reinforcing of itself than it is of the surrounding environment.

Such bubbles do occur in the world, and are a conceptual challenge for scenario developers. For example, one scenario might extrapolate the governance arrangements of the Scandinavian welfare states to global scale, while another might extrapolate the neoliberal orientation of the US. In fact, both exist in the world, but the neoliberal state appears to be in the ascendance globally, at least at present. The current global context thus reinforces neoliberal states more strongly than it reinforces welfare states. Nevertheless, the persistence of the Scandinavian welfare states shows that they are locally stable. With enough of a push, they might be shifted in a neoliberal direction, while in the current global environment a considerably larger push would be needed to move a neoliberal state toward a welfare state.

A system state that is stable only if fluctuations are below a certain threshold is *metastable* rather than stable (see Figure 1). A given scenario can potentially be destabilized by fluctuations. In the ScenarioWizard software (Weimer-Jehle, 2014), which implements CIB, this is indicated by the 'firmness' of scenario descriptors. Firmness, or potential stability, is given by the consistency score for each descriptor.

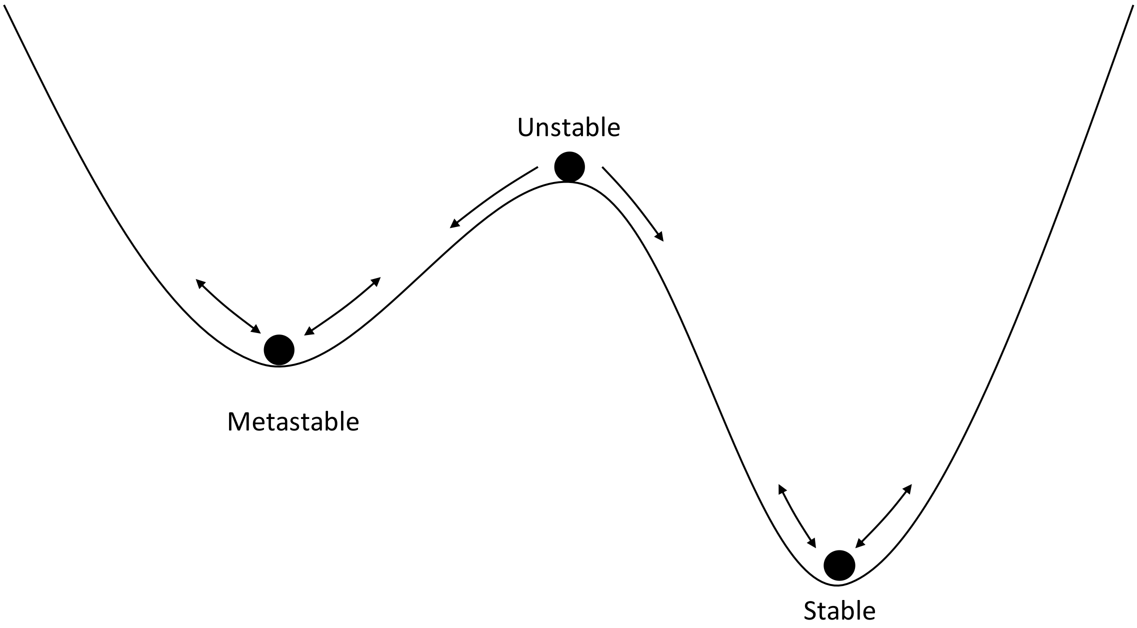

Figure 1:Stable, metastable, and unstable states

SIMULATED ANNEALING

Conceptually, we can identify metastable scenarios using the following algorithm: Start from a consistent scenario; 'turn up the heat' by exploring scenarios that can be reached from the starting point by fluctuations; and finally 'cool down' to find if the system can reach another consistent scenario. This has some parallels to the method of simulated annealing (Kirkpatrick et al., 1983). Although it also has some notable differences, we acknowledge the intellectual debt by referring to the algorithm as ‘CIB simulated annealing’ (CIBSA)[3]:

Algorithm: CIB simulated annealing

1. Define a set of thresholds for each descriptor: $T = \{\Delta_i\}$, where $i = 1,\ldots,N$;
2. Construct a list of candidate scenarios as either: a) all possible scenarios or b) a pseudo-random sequence of distinct scenarios (a larger number yields greater confidence that all attractors will be found);
3. Choose a consistent scenario $\underline{u}$ (a member of K_0 in equation (3));
4. (Heating) Take the next candidate scenario $\underline{v}$ from the list in Step 2, and
    a. If $\theta_{ir'}(\underline{u}) + \Delta_i \geq \theta_{ir}(\underline{u})$ for every descriptor i and $r = u_i$, $r' = v_i$, go to Step 5,
    b. Otherwise, repeat Step 4;
5. (Cooling) Find the attractor of $\underline{v}$ by repeatedly applying the global succession operator S to $\underline{v}$ until the sequence converges;
6. Add the attractor of $\underline{v}$ to the list of consistent scenarios reachable from $\underline{u}$;
7. If the list of candidate scenarios is not yet exhausted, return to Step 4.

Comparing this method to simulated annealing, selecting larger threshold values is analagous to choosing a higher simulated annealing initial temperature. The algorithm then applies a 100% acceptance rate for possible states if they satisfy the condition in Step 4a, and a 0% acceptance rate otherwise. This choice corresponds to a persistent disturbance rather than a temporary ‘shock’ because the alternate state is certain to be reached over a suitably long time[4]. Once a candidate scenario is identified, the system is quenched to discover the local equilibrium that is reached through succession, starting from the candidate scenario.

We applied the algorithm to a hypothetical CIB for a simplified global analysis. The system description includes descriptors for trade (three variants), security (three variants) and economic performance (four variants). This CIB case was developed for this paper as an example, and is not the result of a formal scenario development process. The cross-impact matrix is shown in Table 1, and of the 36 possible scenarios it generates four consistent scenarios, shown in Table 2.

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[3] Python code that implements the CIBSA algorithm is available, with sample files, at https://github.com/sei-international/cibsa.

[4] CIBSA can in principle be extended to the case of shocks. To do this, the algorithm would be run at different thresholds, while the resulting states would be assigned probabilities, declining with the size of the threshold, which reflect the likelihood that the threshold is exceeded.

Table 1: Cross-impact matrix for a small global CIB

	Trade regime			Security stance			Economic performance			
	FT	Ntl	Mix	Rlx	Mod	Alrt	Decl	Stag	Mod	Rpd
Trade regime										
Free trade				1	2	-3	-4	-2	3	3
Nationalist				-2	1	1	3	5	-3	-5
Mixed				2	1	-3	-2	0	4	-2
Security stance										
Relaxed	1	-3	2				-1	-1	1	1
Moderate	1	-2	1				0	1	0	-1
Alert	-2	3	-1				1	2	-1	-2
Economic performance										
Declining	-3	5	-2	-3	1	2				
Stagnant	-2	3	-1	-2	1	1				
Moderate growth	2	-4	2	1	0	-1				
Rapid growth	3	-6	3	-1	1	0				

Table 2: Consistent scenario kernel, as a tableau

	Scenario 1	*Scenario 2*	*Scenario 3*	*Scenario 4*
Economic performance	Stagnant		Moderate growth	
Trade regime	Nationalist		Mixed	Free trade
Security stance	Moderate	Alert	Relaxed	Moderate

We ran the simulated annealing algorithm with thresholds set equal to three for all descriptors ($\Delta_i = 3$ for all i) and found that:

- Scenario 2 is reachable from Scenario 1, and *vice versa* (1 ↔ 2);
- Scenario 3 is reachable from Scenario 4 and *vice versa* (3 ↔ 4);

Requiring scenarios to be stable under ‘heating’ reduces the kernel from four to two scenarios, shown in Table 3. Scenarios 1 and 2 merge, because they readily transform from one to the other, but do not reach Scenarios 3 or 4. Scenario 4 becomes unstable at a threshold of 1, while Scenario 3 is metastable until the threshold is equal to 3, at which point it becomes unstable.

Table 3: Stable scenario kernel, as a tableau

	Scenario 1/2	*Scenario 3/4*
Economic performance	Stagnant	Moderate growth
Trade regime	Nationalist	Mixed/Free trade
Security stance	Moderate/Alert	Relaxed/Moderate

We denote a metastable scenario kernel defined using a set of thresholds T by $K(T)$. It will always have fewer or the same number of scenarios as the consistent kernel K_0. We note that thresholds are relative to the scale of the impact scores, because of the CIB property of local multiplication invariance (Weimer-Jehle, 2009 property XII); multiplying judgement cell $C_{ij}(k,l)$

by a number b_j results in the same set of consistent scenarios, but the impact scores are larger by that multiple. A modified rule applies to a metastable kernel: if each judgement cell $C_{ij}(k,l)$ and threshold Δ_j are multiplied by the factor b_j, then the metastable kernel is unchanged.

Multi-level systems and boundary conditions

We now ask when it is appropriate to apply scenarios constructed at a larger scale as 'boundary conditions' on scenarios developed at smaller scale. Put another way, we ask when a scenario exercise at one scale can be analytically separated from an exercise at another scale. We develop a criterion using the terms, concepts, and notation introduced above. For concreteness, we make use of a multi-scale framework in which large-scale scenarios place boundary conditions on a smaller-scale scenario exercise.

DEVELOPING A CRITERION FOR SCENARIO SEPARATION

A useful and general way of classifying levels of interaction between different scales derives from Emery and Trist's (1965) identification of four types of interactions between an organization and its environment. In the first, the environment is placid and essentially random. Strategy is irrelevant and indistinguishable from tactics. In the second, desirable and undesirable events tend to cluster in non-random groupings. Under these conditions strategy is relevant and distinct from tactics, but the environment remains stable and understandable. In the third type of interaction, the organization faces counterparties like itself; this is the situation envisaged by game theory. The counterparties' reactions to the organization's actions alter the external environment. A new organizational concept becomes relevant, that of operations, which are clusters of tactics with guidelines for how to respond when counterparties take action. In the fourth type, both the organization's actions and those of counterparties impact upon the larger environment in ways that cannot be readily understood; fundamental uncertainty becomes a defining characteristic of organizational life. Organizations invoke social values as guides, and strategy, tactics, operations, and values each play a role.

In an elaboration of Emery and Trist's ideas, van der Heijden (see also Carlsen et al., 2013; 2005, chap. 7) introduced a three-part hierarchy, in which a planning entity (P) interacts directly with a transactional environment (T), which is itself embedded within a contextual environment (C); see Figure 2. The planning entity influences, but does not fully control, its transactional environment. Thus, a firm may have rivals in a local market, while a ministry both competes and coordinates with other areas of government. The planning entity has very limited, often negligible, influence on its contextual environment, partly because of the sheer size of the larger environment and partly because, as noted by Emery and Trist, it cannot anticipate the consequences of its own actions beyond its transactional environment.

The whole-system cross-impact matrix C can consequently be divided into planning entity-only, transactional environment-only, and contextual environment-only sub-matrices, and sub-matrices expressing interactions between those levels[5],

$$C = \begin{pmatrix} C^{pp} & C^{pt} & 0 \\ C^{tp} & C^{tt} & C^{tc} \\ C^{cp} & C^{ct} & C^{cc} \end{pmatrix}. \tag{7}$$

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[5] This is not the only structure consistent with the CIBSA approach. For example, regional scenarios could provide boundary conditions for global scenarios. Schweizer and Kurniawan (2016, p. 327) provide an example in which two non-interacting regions jointly influence the global environment. The modified CIB analysis then generates global scenarios consistent with regional dynamics.

The superscripts indicate the direction in which the impact is assessed. For example, '*tp*' means the impact of descriptors in the transactional environment on descriptors for the planning entity, cf. Figure 2.

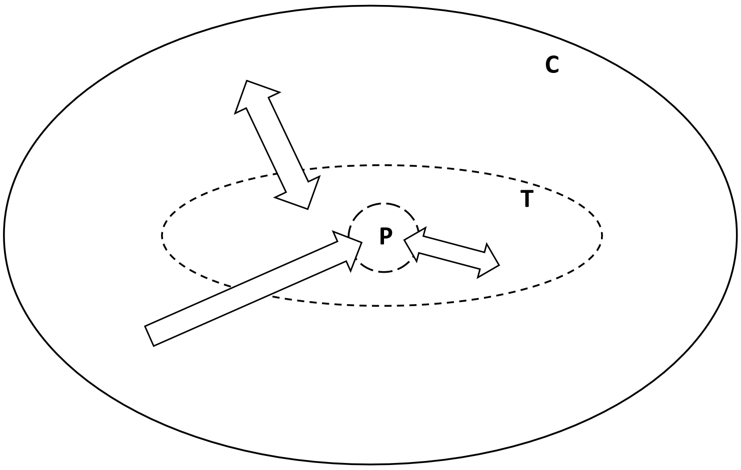

Figure 2: Schematic illustration of a planning entity (P) and its two surrounding environments, the transactional environment (T) and the context environment (C). The arrows represent how interactions are taking place between the three systems (excluding intra-system interactions): the unidirectional arrow represents the sub-matrix C^{cp} in Equation (7) and the outer bidirectional arrows represents C^{ct} and C^{tc} while the inner bidirectional arrow represents C^{pt} and C^{tp}.

We separate an arbitrary whole-system scenario $\underline{u}$ into its components $\underline{u}^p$, $\underline{u}^t$, and $\underline{u}^c$. If the sub-systems have indices $i = 1,\ldots, N_p$, $j = 1,\ldots, N_t$, and $k = 1,\ldots, N_c$, then we can write the whole-system impact balance for descriptor l of sub-system s as

$$\theta^s_{lr}(\underline{u}) = \sum_{i=1}^{N_p} C^{ps}_{il}(u^p_i, r) + \sum_{i=1}^{N_t} C^{ts}_{il}(u^t_i, r) + \sum_{i=1}^{N_c} C^{cs}_{il}(u^c_i, r). \tag{8}$$

Conceptually, this is the most general representation of the full system in terms of sub-systems at different levels, as it allows for an arbitrarily strong interaction between the sub-systems. Note that the first term in Equation (8) is zero for θ^c_{lr} because, by definition, the planning entity has a negligible influence on the contextual environment.

We use the definition for a consistent scenario kernel in equation (3), and apply the condition to a descriptor l in the contextual environment. We require

$$\theta^c_{lr}(\underline{u}) \geq \theta^c_{lr'}(\underline{u}), \tag{9}$$

and from equation (8) we can write this as

$$\sum_{k=1}^{N_c} C^{cc}_{kl}(u^c_k, r) \geq \sum_{k=1}^{N_c} C^{cc}_{kl}(u^c_k, r') + \sum_{j=1}^{N_t} \left(C^{tc}_{jl}(u^t_j, r') - C^{tc}_{jl}(u^t_j, r) \right). \tag{10}$$

Note that terms involving C^{pc} are zero from equation (7). From the earlier discussion, the sums over the planning entity and transactional environment descriptors amount to fluctuations in the contextual environment. If the contextual scenario $\underline{u}^c$ is drawn from a consistent and stable scenario kernel with thresholds Δ_l^c (cf. step 4a in the algorithm) and if

$$\sum_{j=1}^{N_t} \left(C^{tc}_{jl}(u^t_j, r') - C^{tc}_{jl}(u^t_j, r) \right) < \Delta^c_l, \tag{11}$$

then fluctuations driven by local activity will be insufficient to drive the system into another scenario state in the contextual environment.

When inequality (11) holds, we say that the system impacts weakly upon its contextual environment. In that case, we can replace the full set of contextual descriptors with the metastable scenario kernel. The kernel becomes a descriptor, while individual consistent scenarios within the kernel become descriptor states. This considerably reduces the complexity of the analysis, and it allows a contextual scenario kernel – such as a set of global or regional scenarios – to be used consistently in multiple local scenario exercises.

CONSTRUCTING THE REDUCED MATRIX IN THEORY

When the full descriptor set for the contextual environment is replaced with a contextual scenario kernel, the result is a reduced cross-impact balance C', of the form

$$C' = \begin{pmatrix} C^{pp} & C^{pt} & 0 \\ C^{tp} & C^{tt} & C'^{tK} \\ C'^{Kp} & C'^{Kt} & C'^{KK} \end{pmatrix}. \tag{12}$$

To define the sub-matrices, we index the members of a metastable contextual scenario kernel $K(T)$ with thresholds T by m, $n = 1,\ldots, n_K$, where n_K is the number of scenarios in the contextual scenario kernel. The relationship between the contextual environment and itself is reduced to a single judgement group, with judgement cells given by the inner products of pairs of scenarios,

$$C'^{KK}(m,n) = \langle u_m^K \,|\, u_n^K \rangle, \quad u_m^K, u_n^K \in K(T). \tag{13}$$

A given scenario u_m^K in the metastable scenario kernel $K(T)$ is a linear combination of scenarios u_i^c, which are members of the consistent scenario kernel K_0 for the sub-matrix C^{cc} from the full cross-impact matrix shown in equation (7). Denoting the coefficients by α_m^i, we have

$$u_m^K = \sum_{i=1}^{N_c} \alpha_m^i u_i^c, \quad \sum_{i=1}^{N_c} \alpha_m^i = 1. \tag{14}$$

Strictly speaking, scenarios cannot be summed. We apply the weights by analogy to ordinary inner products in the following way,

$$C'^{Kp,t}(m, u_j^{p,t}) = \sum_{i=1}^{N_c} \alpha_m^i \langle u_i^c \,|\, u_j^{p,t} \rangle, \quad C'^{pK}(u_j^p, m) = \sum_{i=1}^{N_c} \alpha_m^i \langle u_j^p \,|\, u_i^c \rangle, \tag{15}$$

and

$$C'^{KK}(m,n) = \sum_{i=1}^{N_c} \sum_{j=1}^{N_c} \alpha_m^i \alpha_n^j \langle u_i^c \,|\, u_j^c \rangle. \tag{16}$$

Aside from the requirement that coefficients should sum to one, they are undetermined; the simulated annealing algorithm only identifies which scenarios should be merged, but not in what proportions.

To assign weights to the scenarios, we note that the simulated annealing procedure takes one scenario into another, or leaves it unchanged. It can also take a scenario into a cycle. The treatment of cycles is challenging, and we do not consider it in this paper[6]. Instead, we look at the

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[6] Conceptually, cycles are no different than stable scenarios for CIBSA. The CIBSA process can be applied to each scenario encountered in a cycle separately and the results combined to judge the likelihood of escaping the cycle through the simulated annealing process. However, it is a comparatively rare phenomenon and adds considerably to the bookkeeping. We chose to not carry it out for the purposes of this paper.

transition probabilities, under simulated annealing, of going from one scenario to another[7]. For example, the probability of passing from Scenario 1 to Scenario 2 under simulated annealing is 3.1%, while the probability of passing from Scenario 2 to Scenario 1 is 2.8%. The matrix of transition probabilities is a stochastic matrix. As we consider an indefinitely long period of time, we apply the transition matrix repeatedly, and in the limit that the number of iterations goes to infinity, the mixture of scenarios approaches a uniform endpoint, independent of the starting point (the ergodic limit of a stochastic matrix). In this case, the mixture is 47% Scenario 1 and 53% Scenario 2. The corresponding figures for the merging of Scenarios 3 and 4 are 86% for Scenario 3 and 14% for Scenario 4. Using these weights, the corresponding matrix C'^{KK} has entries

$$C'^{KK} = \begin{pmatrix} 12.2 & -7.9 \\ -9.4 & 11.1 \end{pmatrix}. \tag{17}$$

This is not regular – it has non-zero diagonal entries – because the contextual scenarios are self-reinforcing. It is also not standardized – the rows do not sum to zero – but can be standardized using the CIB methodology (Weimer-Jehle, 2009 property XI).

WORKING IN PRACTICE

When contextual scenarios are developed using CIB, the judgement group C'^{KK} can be calculated as in equation (13). CIBSA can be applied to the contextual environment in isolation and the reduced matrix applied to the planning and transactional environments. This procedure is justified when the inequality (11) holds, meaning that the system impacts weakly upon its contextual environment. To test for the inequality and to make the reduced matrix in equation (12), the full matrix must be specified.

In practice, constructing a full matrix is either impractical, because of time required to populate the matrix, or impossible, because the contextual scenarios were constructed without using CIB. In these cases, detailed contextual descriptors are not available, values must be assigned based on expert judgement. This begs the question who these experts might be. As noted by Wiemer-Jehle (2006, pp. 337–338), the disaggregated approach used in CIB is meant precisely to manage the ‘mental integration’ required to anticipate indirect impacts in complex systems. Similarly, Emery and Trist (1965) argue that a planning entity cannot anticipate the indirect consequences of its actions as mediated through the larger environment.

We justify our approach through two arguments. First, our intent is to provide a theoretical foundation for an increasingly common method: using global scenarios as ‘boundary conditions’ on local scenarios. We have shown that there are conditions under which this procedure is justified, and by extension conditions under which it is not justified. Roughly, it can be applied when the influence of the planning entities’ transactional environment upon the contextual environment is below a threshold, while the contextual scenarios are stable against disturbances up to that threshold. This rough and qualitative version of the test can be carried out by the planning entity. For example, if a Caribbean island such as Jamaica has identified as its contextual environment the Caribbean Community (CARICOM), regional experts might say that CARICOM has little influence on the trajectory of the global economy. By contrast, Denmark, while having little influence by itself on the global economy, is an EU member state, which does have substantial influence. Applying global economic scenarios as boundary conditions is justified for Jamaica, and at least questionable for Denmark. The crucial question is whether the

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[7] A simpler alternative, which may be suitable for some analyses, is to use the basins of attraction of the scenarios as weights.

EU can shift the world from one global scenario into another. If that is judged to be possible, then regional scenarios may be applied as boundary conditions on a global scenario exercise, as in the example presented in Schweizer and Kurniawan (2016).

Second, the separation of the local environment into the hyper-local environment of the planning entity and the broader transactional environment is a step toward disaggregated analysis. While the aggregation method described in this paper can be used for any hierarchical system, and CIBSA can be used for any CIB whatsoever, the planning-transactional-contextual separation has proven to be particularly useful (Carlsen et al., 2013; van der Heijden, 2005, chap. 7). Continuing the examples from the previous paragraph, the CARICOM Secretariat's Office of Trade Negotiations helps to coordinate member states' engagement in international trade agreements. The influence of CARICOM on global negotiations, and the influence of global agreements on the region, can be assessed by regional experts. Moreover, experts in Jamaica and the region can assess the mutual influences between the national government and CARICOM. This separation allows for indirect influences from the planning entity through its transactional environment to the contextual environment and back again. Thus, the burden of 'mental integration' is reduced by interposing the transactional environment between the planning entity and its contextual environment.

If expert judgement is used to assign scores to the global scenario descriptor, then unlike a regular CIB analysis, the diagonal elements are non-zero, and must be large enough to prevent changes in the transactional environment from driving the contextual environment into a new state. If the system impacts weakly upon the contextual environment – that is, the CIBSA thresholds have been set high enough to capture variations in the transactional environment, as in expression (11) – then we can find a sufficient condition for the stability of the contextual environment. We start with equation (10), setting $r = u_l^c$ and $r' = v_l^c$, and summing over l. Using the definition of the inner product in equation (1), we have

$$\langle u^c \,|\, u^c \rangle \geq \langle u^c \,|\, v^c \rangle + \sum_{l=1}^{N_c} \sum_{j=1}^{N_t} \left(C_{jl}^{tc}(u_j^t, v_l^c) - C_{jl}^{tc}(u_j^t, u_l^c) \right). \tag{18}$$

From equation (11), we then have

$$\sum_{l=1}^{N_c} \sum_{j=1}^{N_t} \left(C_{jl}^{tc}(u_j^t, r') - C_{jl}^{tc}(u_j^t, r) \right) < \sum_{l=1}^{N_c} \Delta_l^c. \tag{19}$$

If we impose a more stringent condition than in equation (18), namely that

$$\langle u^c \,|\, u^c \rangle \geq \langle u^c \,|\, v^c \rangle + \sum_{l=1}^{N_c} \Delta_l^c, \tag{20}$$

then it provides a sufficient, but not necessary, condition for ensuring that fluctuations will not drive drive the system from scenario u^c to scenario v^c. Because we wish this to hold for transitions in either direction for the scenario kernel, we require the off-diagonal elements to satisfy

$$\langle u_m^c \,|\, u_n^c \rangle + \sum_{k=1}^{N_c} \Delta_k^c \leq \min\left(\langle u_m^c \,|\, u_m^c \rangle, \langle u_n^c \,|\, u_n^c \rangle \right), \quad m \neq n. \tag{21}$$

When this condition holds, a CIBSA exercise using the judgement group C'^{KK} would find that scenario m cannot be reached from scenario n, and *vice versa*.

Even if detailed contextual descriptors are available, the analytical separation of the contextual environment from the rest means that judgements need be made only for the reduced matrix in equation (12), and not the (potentially much larger) matrix in equation (7).

Illustrating the method

We illustrate the method developed above with a hypothetical application to a country acting within a global context. The planning entity is taken to be a national government, while its transactional environment is its near neighbors (the region in which it is located). The global descriptors and states are the same as the ones used earlier to demonstrate the CIB simulated annealing algorithm. The full set of descriptors and states is presented in Annex 1. The cross-impact matrix for the full system[8] includes some impacts from regional to global level, but the gap between the lowest and highest possible scores is equal to 2. So, for thresholds set equal to 3 at global level, which we did earlier in the paper, the condition in (11) is satisfied.

ANALYZING THE FULL MATRIX

We applied the CIB algorithm using the ScenarioWizard software, running in standard mode in which all possible scenarios are sampled. The system gives rise to 20 consistent scenarios. Across the full set, four combinations of global descriptor variants make an appearance; these are recorded in Table 4. This is a different set from the four consistent global scenarios shown in Table 2. However, they map to the two stable and consistent scenarios shown in Table 3. We find that Scenario W1 maps to Scenario 1/2, while Scenarios W2, 3 and 4 map to Scenario 3/4. The only variant missing is global Scenario 1 from Table 2, a combination of a stagnant economy in a nationalist trade regime with a moderate security stance.

Table 4: The four global descriptor variant combinations in the 20 whole-system scenarios

	Scenario W1	*Scenario W2*	*Scenario W3*	*Scenario W4*
Economic performance	Stagnant	Moderate growth		
Trade regime	Nationalist	Mixed		Free trade
Security stance	Alert	Relaxed	Moderate	

ANALYZING THE REDUCED MATRIX

We constructed a reduced cross-impact matrix by collapsing the global descriptors to a single global descriptor corresponding to the stable Scenarios 1/2 and 3/4 in Table 3. We calculated matrix entries by computing inner products, as in equations (15) and (16), and setting weights using the ergodic limit of the stochastic transition matrix from the CIBSA process, as described above. This resulted in fractional values, which we rounded to the nearest integer. Finally, we regularized the matrix using the functionality of the ScenarioWizard software.

The reduced cross-impact matrix produced 15 consistent scenarios. The full set contained 18 unique scenarios after global scenarios of type 3/4 were merged, as two of the 20 scenarios in the full set were found to have an equivalent pair after merging. The remaining scenarios were comparatively minor, in that their weight (Weimer-Jehle, 2009 property IX) – the number of starting scenarios that lead to the scenario's basin of attraction under the succession operation – constituted less than 5% of the weights of all 20 consistent scenarios of the full matrix. A further scenario appeared in the reduced set, with 3% of the basin of attraction, which did not appear in the full set.

In the reduced analysis, we expect the basins of attraction of global Scenarios 1/2 and 3/4 to be split roughly equally if the criterion for analytical separation holds, because one should not be reachable from the other. They will not be in exactly equal proportions because there is an odd

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[8] The ScenarioWizard file for the system, which includes the cross-impact matrix, is available on GitHub: https://github.com/sei-international/cibsa/tree/master/sample_files.

number of scenarios. This expectation is met. In the run used for this paper, we found that 50.1% of all scenario weights for the system led to Scenario 1/2, while 49.9% led to Scenario 3/4.

COMPARING THE REDUCED AND FULL ANALYSES

The 13 national and regional scenarios that appear in combination with global scenarios in the full and reduced analyses are listed in Annex 2, labeled A-M. As shown in Table 5, the basins of attraction for national and regional scenarios do not match. Thus, merging scenarios changes the dynamic behavior of the system, even as it preserves consistency.

Table 5: Basins of attraction of national/region scenarios as proportion of the total

	Scenario 1/2			Scenario 3/4	
National/ Regional	Reduced (%)	Full (%)	National/ Regional	Reduced (%)	Full (%)
A	6.2	12.4	B	0.2	3.8
B	2.0	5.1	H	0.0	0.2
C	63.5	43.2	D	1.1	23.7
D	12.0	27.5	I	0.0	1.2
E	11.1	8.6	K	0.0	12.4
F	3.4	2.3	L	5.9	0.0
G	1.4	0.7	E	68.1	43.2
A	6.2	12.4	F	12.9	43.2
			G	0.7	43.2
			M	11.4	15.1

Discussion

In the foregoing we have constructed a criterion for when large-scale scenarios can be applied as ‘boundary conditions’ on scenarios at smaller scale. Essentially, the criterion requires a large-scale scenario kernel to be stable under perturbations generated at lower scale – that is, scenarios at larger scale must be ‘metastable’. We adopted the concept behind the optimization method of simulated annealing to determine what consistent scenarios become merged under small perturbations and thus can be combined in a metastable scenario kernel.

We demonstrated the approach using a full multi-scalar cross-impact matrix (CIM), but this may not be necessary in practice. The utility of the boundary method approach is that a reduced CIM can be used instead of the full one. If the large-scale scenario kernel is sufficiently robust that its members are metastable against changes at smaller scale, then the large-scale kernel can be used as a descriptor in the smaller-scale scenarios. The large-scale scenario then becomes a driver of developments at smaller scale. In the CIB formalism this can be reflected by using an irregular judgement group for the large-scale scenarios (one with non-zero diagonal entries) to capture the self-reinforcing nature of each metastable large-scale scenario.

Applying the method allows for an indirect influence from small to large scale, mediated by the transactional environment. While the planning entity of van der Heijden (2005) only influences its transactional environment (by definition), and not its contextual environment, developments in the transactional environment can, in principle, influence the contextual environment. Scenarios for the contextual environment can be applied as boundary conditions – in the sense that dynamics in the transactional environment will not drive the system from one contextual scenario to another – if the total impact score from an arbitrary scenario in the transactional environment is less than the minimum difference between the diagonal and off-diagonal elements in the judgement section corresponding to the contextual scenario kernel. Referring to equation

(21), this condition is satisfied when the thresholds are set to the maximum cross-impact of a scenario for the transactional environment on a scenario for the contextual environment.

In the concrete application of the theory, we found that the consistent scenario set was substantially reproduced in the reduced analysis. Those scenarios that were found with the full CIM but not the reduced one had small basins of attraction and could therefore be neglected in many (perhaps most) scenario exercises[9]. We also found the contextual (global) scenarios to be stable in the reduced analysis, as expected.

The basins of attraction of the consistent scenarios in the reduced analysis were substantially but not fully identical to those of the full analysis. This suggests that the dynamic interpretation of the CIB method becomes less reliable when scenarios are merged. Despite this reservation, the results give confidence in the concept of applying large-scale scenario kernels as boundary conditions, and provide a concrete way to implement them in a smaller-scale CIB analysis.

Conclusions

In this paper we have proposed a technique for implementing nested scenarios for multi-level systems. Using the Cross-impact Balance (CIB) formalism, we derived a criterion for assessing whether scenario exercises at different scales can be analytically separated, such that scenarios at one scale can act as 'boundary conditions' on a scenario exercise at another scale. Schweizer and Kurniawan (2016) pursue a similar goal, by making use of sparse structure of multi-scale cross-impact matrices rather than aggregation, as we do in this paper.

In the course of the derivation we extended the dynamic interpretation of CIB to encompass systems subject to randomly fluctuating external environments. We introduced the concept of 'metastable' states and an algorithm to discover them. Insights from applying the method to a hypothetical example provided guidance for the application of large-scale scenarios as boundary conditions in a small-scale CIB exercise.

The paper demonstrates the utility of CIB for formally addressing questions in Futures Studies. In common with Schweizer and Kurniawan (2016), it also provides theoretical support for the compelling but vague notion of boundary conditions in the context of scenario development, and guidance for carrying out nested scenarios when cross-scale interactions are likely to be important. Specifically, using concepts introduced by Emery and Trist (1965) and van der Heijden (2005), the paper formalizes the intuition that high-level 'contextual' scenarios can be applied as boundary conditions on local studies when local dynamics are unlikely to drive the contextual environment from one stable scenario to another.

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[9] An exception is a risk assessment that considers unlikely but potentially impactful outcomes (see Schweizer and Kurniawan, 2016, p. 330).

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Annex 1: Descriptors and states

National descriptors and states

- International orientation (NINT): 1) Insular (Ins), 2) Regionalist (Reg), 3) Globalist (Glb)
- Trade orientation (NTRD): 1) Protectionist (Prot), 2) Free-trade (FT), 3)Mixed (Mix)
- Domestic economy (NDOM): 1) Welfare (Wel), 2) Market (Mrkt), 3) Mixed (Mix)
- Security stance (NSEC): 1) Relaxed (Rlx), 2) Moderate (Mod), 3) Alert (Alrt)
- Economic performance (NECO): 1) Decline (Decl), 2) Stagnation (Stag), 3) Moderate growth (Mod), 4) Rapid growth (Rpd)
- Inequality (NINEQ): 1) Low (Low), 2) Moderate (Mod), 3) High (Hi)
- Social stress (NSTRS): 1) Low (Low), 2) Moderate (Mod), 3) High (Hi)
- Urbanization (NURB): 1) Slow (Slow), 2) Moderate (Mod), 3) Rapid (Rpd)

Regional descriptors and states

- International orientation (RINT): 1) Insular (Ins), 2) Regionalist (Reg), 3) Globalist (Glb)
- Trade orientation (RTRD): 1) Protectionist (Prot), 2) Free-trade (FT), 3) Mixed (Mix)
- Security stance (RSEC): 1) Relaxed (Rlx), 2) Moderate (Mod), 3) Alert (Alrt)
- Economic performance (RECO): 1) Decline (Decl), 2) Stagnation (Stag), 3) Moderate growth (Mod), 4) Rapid growth (Rpd)
- Regional cooperation (RCOOP): 1) Antagonistic (Antg), 2) Weak (Wk), 3) Moderate (Mod), 4) Strong (Str)
- Regional migration (RMIG): 1) Minor (Mnr), 2) Moderate (Mod), 3) Substantial (Sbst)

Global descriptors and states

- World trade structure (WTRD): 1) Free-trade (FT), 2) Nationalist (Ntl), 3) Mixed (Mix)
- Security stance (WSEC): 1) Relaxed (Rlx), 2) Moderate (Mod), 3) Alert (Alrt)
- Economic performance (WECO): 1) Decline (Decl), 2) Stagnation (Stag), 3) Moderate growth (Mod), 4) Rapid growth (Rpd)

Annex 2: Descriptor variants for national and regional scenarios

	National/Regional Descriptor												
Scenario	NINT	NTRD	NDOM	NSEC	NECO	NINEQ	NSTRS	NURB	RINT	RTRD	RSEC	RECO	RCOOP	RMIG
A	1	1	2	3	2	3	3	1	1	1	3	1	1	1
B	1	1	2	3	2	3	3	1	1	1	3	2	1	1
C	1	1	2	3	2	3	3	1	1	1	3	3	1	1
D	1	1	3	3	2	2	3	1	1	1	3	1	1	1
E	1	1	3	3	2	2	3	1	1	1	3	2	1	1
F	1	1	3	3	2	2	3	1	1	1	3	3	1	1
G	2	2	1	2	3	2	1	2	2	2	2	3	4	2
H	2	2	3	2	3	2	2	2	2	2	2	3	4	3
I	2	2	3	2	3	2	2	2	2	3	2	3	4	3
J	2	3	3	2	3	2	2	2	2	3	2	3	3	2
K	2	3	3	2	3	2	2	2	2	3	2	3	4	2
L	2	3	3	2	3	2	2	2	2	3	2	3	4	3
M	3	3	3	3	3	2	3	2	3	3	3	3	1	2