Summary of Key Measures for Characterizing Organizational Architectures

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What is here

This file contains the following information:

1. A discussion of how the measures listed here were chosen.
2. A set of measures rank ordered, with name, verbal discussion, the mathematical measure, and where appropriate a question that can be used on a questionnaire to capture functionally comparable data. The measures are divided into measures of organizational architecture and measures of outcomes.
3. Discussion of what data we needed to test the models we have developed at CMU.
4. The cite for the location where the C code for these and other measures.
5. The cite where you can go to get UCINET – a statistical analysis tool for network (matrix) data.

Measures

How were the measures chosen?

First a large set of measures we collected. This set included: all commonly used social network measures, measures of hierarchy, measures of tasks (from OR), measures of organizational design (Galbraith, Thompson, Malone). In addition we got from Sue Hutchins and Elliot Entin the set of terms of art (such as unity of command) in the navy. We developed C code for calculating these measures given network data. We then developed the notion of the meta-matrix – see Figure 1.

The Meta-matrix is a conceptual device for laying out the relation among types of networks and for determining where we have insufficient measures. A huge number of measures exist in the literature. Each of these can be laid out relative to the meta-matrix showing what data is needed to calculate what measure. In figure 2, a small sample of these measures and their relation to the cells in the meta-matrix that take only personnel, resources and tasks in to account. When this is done, we see that we have most measures for dealing with square matrices – typically coming from social networks – each of which needs to be re-interpreted if applied to nodes other than people.

	People	Knowledge	Resources	Tasks	Organizations
People Relation	**Social Network** *Who knows who*	**Knowledge Network** *Who knows what*	**Capabilities Network** *Who has what resource*	**Assignment Network** *Who does what*	**Work Network** *Who works where*
Knowledge Relation		**Information Network** *What informs what*	**Skills Network** *What knowledge is needed to use what resource*	**Needs Network** *What knowledge is needed to do that task*	**Competency Network** *What knowledge is where*
Resources Relation			**Substitution Network** *What resources can be substituted for which*	**Requirements Network** *What resources are needed to do that task*	**Capital Network** *What resources are where*
Tasks Relation				**Precedence Network** *Which tasks must be done before which*	**Market Network** *What tasks are done where*
Organizations Relation					**Inter-Organizational Network** *Which organizations link with which*

Figure 1. Extended Meta-Matrix

	Individual	**Resource**	**Task**
Individual	*Size *Level *Span of control *Network Density *Conductivity *Degree Centralization *Betweenness *Connectivity *Efficiency *Least Upper Boundedness	*Consensus *Resource Specialization *Access Redundancy	*Workload *Assignment Complexity
Resources		*Size *Network Density *Substitutes	*Needs Complexity
Task			*Size *Network Density *Longest Path

Figure 2. Illustration of how measures relate to cells in the Meta-Matrix

Then, for each measure, its position in the extended meta-matrix was determined; i.e., what cell or cells were used to calculate that measure. For each measure, if it existed in a single cell (i.e., had been traditionally collected only for data in one cell) we created an analog for other cells of that type (type = square or rectangular). For any cell without a measure we created measures. We then created a series of measures that used data from multiple cells. This gave a large set of measures.

For each of the measures in this large set of measures, if there did not already exist a way to mathematically calculate that measure using network data we developed a mathematical formula. Each of these measures were then calculated given data from the CMU simulations and from data captured during the NPS experiment 4.

Complication 1: It is important to realize that the meta-matrix exists in at least 3 forms – the potential network (what can connect to what), the actual network (what actually happens), and the perceived network (what an individual thinks happens). As to the perceived network there is one such perception for each individual in the group/team/organization. As an example of these three forms, we have under the social network cell – the communication network. It's potential form is who can communicate with whom. The actual form is who does communicate with whom. Who does communicate with whom is typically a subset of who can communicate with whom. The perceived form is, e.g., for Daniel, who does Daniel think communicates with whom.[1] Each of the measures in the large set of measures can be calculated on the potential, the actual, and the perceived.

Complication 2: It is important to realize that the meta-matrix can, but need not, change over time. Thus it is often useful to capture the meta-matrix each time period, or at the beginning and end of a mission, or every so many time periods, or after each major event. Each of the measures in the large set of measures can be calculated on the meta-matrix at each time period. Plotting these measures over time is often a useful way to examine change behavior.

Calculating this large set of measures on the potential, actual and perceived meta-matrix at multiple points in time provides an ungainly number of measures. To locate a subset of measures of organizational architecture for researchers interested in teams or command and control we took the large set of measures and calculated them on the actual network, at the beginning, after a major event, and at the end for thousands of organizations including those comparable to those ran in experiment 4, standard stylized organizational architectures studied in the organizational theory literature, and a random set chosen uniformly over the set of possible architectures of small to moderate sized teams. This lead to a matrix of data – measures by organization. We then factor analyzed the resulting data. Large numbers of measures factored together. We then selected one or

[1] Lots of research demonstrates that perception does not equal reality, that two individuals often disagree on whether or not they communicate, and the group's common view is often distinct from the reality. We have measures to capture all of these differences.

two measures for each factor such that a) that measure loaded high on that factor, b) exhibited variance across the organizations studied, and c) where there were measures whose loadings were about equal we chose the measure that had more frequently been used in the literature. The result was the set of measures in table 1.

For the formulas given in this report let
I: The number of personnel
R: The number of resources
T: The number of tasks
i: a specific individual
r: a specific resource
l: a specific task
t: time period
AuN: authority network (in social network personnel by personnel)
ComN: Communication network (in social network personnel by personnel)
CN: Capabilities network (personnel by resources)
AN: Assignment network (personnel by tasks)
KN: Knowledge network (personnel by knowledge)
NN: Needs network (resources by tasks)
PN: Precedence network (tasks by tasks)
$SP_{ij}(XN)$: Shortest path between nodes i and j (trace the arrows from one node to another – the path that uses the fewest number of arrows is the shortest path, it's length is the number of arrows) in the XN network.
Perf(t): % of tasks done correctly by team during time period t (this might be the firsthalf of the mission).

All networks in the meta-matrix are assumed to contain directed links (think of this as a graph – there are arrows heads on the lines).

Table 1. Measures of Organizational Architecture

Variable	Meaning	Mathematical Formula	Questionnaire
Size	Number of personnel.	I	How many people are in your team?
Level	The number of levels in the hierarchy in the authority network.	For AuN for all pairs of individuals calculate the shortest path $SP_{ij}(AuN)$, then choose from these the longest of the shortest paths.	Think of the organizational chart for your team. How many levels are there in that chart?
Span of Control	Average number of subordinates per supervisor.	For AuN for each agent who has 1 or more subordinates (a supervisor), sum the number of subordinates, then divide by the number of supervisors.	What is the average number of subordinates per supervisor?
Least Upper Boundedness	How far disagreements among personnel need to go up the chain of command	LUB = 1 - V / MaxV, where V is the number of pairs of points that have no LUB in each component summed across all components, and MaxV is the maximum number of pairs of points that could possibly have no LUB.	If there is an exception that needs to be handled, or if you need authorization for a

	to be resolved.		project between personnel in two or more divisions, or if there is a conflict between personnel in two or more divisions how far up the chain of command do you need to go to get a resolution?
Resource Load	Average number of resources per agent.	$(\Sigma^{I}_{i=1}\Sigma^{R}_{r=1} CN_{ij})/I$	What is the average number of resources per person?
Consensus	Average degree of agreement in the group.	Assume a classification choice task of length R. Assume the number of such tasks is T*X. Generate T*X binary strings, randomly, with 50% likelihood of 1 in any cell. These are ST_{lxr} s.t. $ST_{lxr} = 1$ if for task l, for subtask x, for resource r has a positive value and 0 otherwise. For each task l (from 1 to T) for each agent i (from 1 to I) if agent is assigned to that task $AN_{il}=1$ then for each of the X binary strings for each resource if the agent has that resource $CN_{ir}=1$ then add up the value. If the agent has access to more resources for that task and subtask that are 1 than 0, then the agent's decision is 1 else it is 0; i..e., if $(\Sigma^{X}_{x=1}\Sigma^{R}_{r=1} CN_{ir} ST_{lxr})/(\Sigma^{R}_{r=1} CN_{ir}) >= .5$ the individual's decision is a 1 else it is a 0. Now for all the individuals assigned to the task, find out if more have a 1 or a 0 decision. This is the majority. Calculate the size of the majority for each task and subtask. Sum this up. Divide by T*X*I.	On average, for any given decision, approximately what fraction of the team typically agrees?
Assignment Redundancy	Average number of excess personnel (more than 1) assigned to the same task.	Let $x_l = \Sigma^{I}_{i=1} AN_{it}$. If $x_l >= 1$ then $x_l = x_l - 1$ else it is left alone. Then assignment redundancy = $(\Sigma^{T}_{l=1} x_l)/T$.	On average how many personnel are assigned to each task?
Need for Negotiation	The extent to which personnel need to negotiate with each other because they do not have the resources to do the task to which they are assigned.	Need for negotiation = number tasks need resources / T Number of tasks need resources = number of tasks where there is a –1 in the row in this matrix: NN' – (AN'*CN)	On average, across all tasks, how often do people need to communicate with others to ensure that the resources needed to do that task are available?
Cognitive Load	A complex measure taking into account the number of others, resources, tasks the agent needs to manage and the communication needed to engage in such activity.	Cognitive load: defined for each person, which is equal to (1+2+3+4+5+6)/6 1. # of people person i interacts with / total # of people in the group; 2. # of resources person i manages / total # of resources 3. # of tasks person i is assigned to / total # of tasks 4. sum of # resources required by the tasks person i does / (total # of tasks * total # of resources) 5. sum of # people who do the same tasks person i does / (total # of tasks * total # of people)	On average, how much mental effort do people need to expend to do a typical task?

		6. sum of negotiation needs person i needs to do for each task / total possible negotiations $CL_i = (\frac{\sum_{j=1}^{N}\alpha_{ij}}{N} + \frac{\sum_{r=1}^{R}C_{ir}}{R} + \frac{\sum_{t=1}^{T}A_{it}}{T} + \frac{\sum_{t=1}^{T}\sum_{r=1}^{R}A_{it} \wedge N_{rt}'}{R*T} + \frac{\sum_{t=1}^{T}\sum_{i=1}^{N}A_{it} \wedge A_{it}'}{N*T} + \frac{\sum_{t=1}^{T}\sum_{r=1}^{R}(C_{ir} - A_{it} \wedge N_{rt}')}{R*T})/6$	
Under Supply	The extent to which the resources needed to do the task are unavailable in the entire organization.	Under Supply - average number of needed resources per task This is the number of –1 in the matrix: NN' – (AN'*CN) Divided by the number of tasks, T.	On average, for a typical task, are the needed resources available?
Task Congruence	Task congruence takes into account the number of errors in whether an individual has access to the resources that are actually needed to do the task to which the individual is assigned.	1 – (The Hamming Distance between CN'AN and NN)/RT	Is there anyone who has nothing to do? Do personnel have the resources they need to do the tasks to which they are assigned?

We then took these measures and used them to predict outcomes in both the CMU models and in experiment 4. We used 4 different outcome measures – see table 2. When we did this, the measure level in table 1 dropped out as being less predictive.

Table 2. Measures of Organizational Performance

Variable	Meaning	Mathematical Formula	Questionnaire
Common Operational Picture	The fraction of the available information that is shared by everyone.	$(\Sigma^{K}_{k=1}((\Sigma^{I}_{i=1} KN_{ik})/ I =1)/K$	How much information does the group share? Or ask each person, for a critical event, to tell you what each other was doing and compare this with what they say they are doing? (Like Entin's measure of awareness)
Adaptability	The percentage difference in performance as measured at the beginning and end of the mission.	((Perf(t-1) – Perf(t))/Perf(t)) * 100	Was the initial level of performance maintained or go up over the course of the mission? or What is the performance at the beginning? What is the performance at the end? Then calculate the percentage

			difference.
Sustainability	The standard error in performance. The lower the value the more sustainable the overall performance.	$((Perf_1(t) – Mean(Perf(t)))^2)T(t)$	Over the course of the mission is there a fairly consistent level of performance?
Performance (Accuracy)	Fraction of tasks finished correctly..	Perf(t)= (Number of tasks correctly solved in that time period/Number of tasks in that time period)*100	How well is the group performing? What fraction of the subtasks is the organization correctly performing?

What measures do we suggest for experiment 8?

A set of measures with name and meaning are listed in table 3. We have found these measures to be useful across many scenarios.

Table 3. Key Measures

Variable	Meaning
Size	Number of personnel.
Span of Control	Average number of subordinates per supervisor.
Least Upper Boundedness	How far disagreements among personnel need to go up the chain of command to be resolved.
Resource Load	Average number of resources per agent.
Assignment Redundancy	Average number of excess personnel (more than 1) assigned to the same task.
Need for Negotiation	The extent to which personnel need to negotiate with each other because they do not have the resources to do the task to which they are assigned.
Cognitive Load	A complex measure taking into account the number of others, resources, tasks the agent needs to manage and the communication needed to engage in such activity.
Under Supply	The extent to which the resources needed to do the task are unavailable in the entire organization.
Task Congruence	Task congruence takes into account the number of errors in whether an individual has access to the resources that are actually needed to do the task to which the individual is assigned.
Common Operational Picture	The fraction of the available information that is shared by everyone.
Adaptability	The percentage difference in performance as measured at the beginning and end of the mission.
Performance (Accuracy)	Fraction of tasks finished correctly..

Testing the CMU Models

Discussion of what data we need to test the models we have developed at CMU. The models we have developed have been and can be tested and validated at multiple levels. Computational models can be validated at many levels. Four that are particularly relevant to this project are: detailed, probabilistic, high level and summary. At the detailed level that actual and potential networks for the entire meta-matrix and several measures of performance, task shedding, and perceived workload are collected. This is the most complete level, with such data we can regenerate any of the measures identified above as well as dynamic aspects of the group. Probabilistic networks are estimates of the probability of their being a tie between any two nodes for each of the networks in the meta-matrix and several measures of performance, task shedding, and perceived workload are collected. From this data probabilistic estimates of any of the measures previously identified can be constructed. At the high level, information about the pattern of ties is used to define a stylized structure of that type (e.g., hierarchy versus team) and several measures of performance, task shedding, and perceived workload are collected. From this data relative differences in the levels of the various measures can be constructed. Finally, rather than data on the networks per se, data on the summary measures such as answers to the questions listed in column 4 in table 1 and several measures of performance, task shedding, and perceived workload are collected. This can be used to reverse engineer a set of possible networks. The models can be tested at any of those levels, however the fidelity of the results and the range of possible results will vary.

Level of Data	Fidelity	Range of Results	Where has Construct-o Validation occurred	Where has Orgahead Validation occurred	Where has ORGMEM Validation occurred
Detailed actual networks	High = 4	High = 4	yes	no	no
Probabilistic networks	3	3	yes	yes	no
High level structure (stylized networks)	2	2	no	yes	no
Summary level	Low = 1	Low = 1	yes	yes	yes

Ideally what we would like from the DDD via a postprocessor is the potential and actual
Authority network,
Communication network (such that each cell is the number of messages sent)
The assignment network
The needs network
The precedence network
The capabilities network

If it is a two phase task, or an experiment where things switch in the middle
Then we would like the actuals for each phase separately

We would like any performance measures you can get – particularly if there is one related to accuracy.

We would like any measures of awareness or mutual awareness that you can get.

C Code

We began to develop stand-alone C code for each of these measures in the large set of measures such that other research teams could plug that C code in to their programs. This set of C sub-routines is now finished for all of the primary measures (including all of those listed in this document) and many of the secondary measures.

The cite for the location where the C code for the measures identified above and others that we have developed is

http://legba.hss.cmu.edu/netstat

. There is also C code for many standard social network measures. There are also routines for, given a set of matrices (e.g., communication networks for multiple groups or across many time periods) running cluster analysis, MDS, and other standard statistical procedures but on networks rather than the traditional "columns" of data.

UCINET

UCINET is a professionally developed and maintained software package for analyzing network data. It includes facilities to manipulate matrices. It also includes a fairly comprehensive set of measures that have been developed over the past 4 decades to analyze social networks. The data that can be used here are either square ore rectangular matrices with either one or two types of nodes. Examples are – communication networks among people, alliance networks among companies, attendance matrices of who attended what event. Included in the package are a set of sample data, help routines, etc. Each of these measures has been used in multiple papers, taught in courses, etc.

The cite where you can go to get UCINET – a statistical analysis tool for network (matrix) data is the INSNA cite. Also the cite for Steve Borgatti borgatts@bc.edu.

References on Measures

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