From Hierarchies to Heterarchies: Application of Network Optimization to Design of Organizational Structures *

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ABSTRACT

Hierarchical organization structures, in which the authority to resolve the most frequent types of exceptions is retained by supervising DMs, can function effectively for routine tasks with little mutual interdependence among tasks. However, if tasks to be performed by the organization are complex, unpredictable, and highly interdependent, the supervising DMs will be overloaded with coordination overhead associated with the processing of frequent exceptions. In this paper, we propose a methodology to design networked organizational structures, which allow the lateral delegation of authority and inter-level flow of communication and control, as well as resource sharing. The approach is based on extending our 3-phase design process to include optimal information flow routing and topological network design subproblems within the design process.

1. Introduction*

Contingency theorists (e.g., [3]) argue that there is no one best way to organize: the optimal structure for an organization depends on the attributes describing its task and its environment. When the information required to execute a task is lacking at a node responsible for it, and *exceptions* arise – that is, a decision-maker must communicate with a supervisor or a peer to obtain the requisite information to complete the task, the formal channels that can be used to communicate these exceptions are defined by hierarchical or legitimate lateral relationships. The performance of such an organization degrades when:

(a) A channel used to communicate exceptions becomes overloaded with exceptions; or

(b) One or more nodes (DMs) cannot process the assigned tasks and exceptions as rapidly as they occur.

Hierarchical organization structures, in which the authority to resolve the most frequent types of exceptions is retained by supervising DMs, can function effectively for routine tasks with little mutual interdependence among tasks. However, if tasks to be performed by the organization are complex, unpredictable, and highly interdependent, the supervising DMs will be overloaded with coordination overhead associated with the processing of frequent exceptions. Two solutions can be seen for this problem:

(a) Decentralization of decision-making authority – it reduces the number of exceptions to be processed by supervising DMs in the organization;

(b) Addition of new and advanced – IT21 tools to provide shared situation assessment – they increase the information-processing capacity of an organization.

The two solutions are not mutually exclusive. Indeed, decentralization of decision-making authority is only possible due to advances in information technology. The latter has radically changed the fundamental coordination constraints on organizations. For example, by making communication and data storage much cheaper and by facilitating previously impractical interactions across time and/or space, the IT21 tools

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have made it feasible for new organizational forms to emerge, some of which may be more effective than the traditional ones. Indeed, it was hypothesized [7] that optimal fractal dimensionality of organizations is equivalent to that of living organisms.

We propose a methodology to design networked organizational structures, which allow lateral delegation of authority and multi-level flow of communication and control, as well as resource sharing. The approach is based on extending our 3-phase design process to include optimal information flow routing and topological network design subproblems within the design process. In this paper, we propose a methodology to design networked organizational structures, which allow the lateral delegation of authority and inter-level flow of communication and control. These organizational structures are better able to cope with complexity, uncertainty and interdependence among tasks than the hierarchical ones.

The rest of the paper is organized as follows. Section 2 outlines the motivation for this research. Section 3 briefly described the 3-phase design process, the output variables of the design process, and types of communications among DMs. Section 4 presents an introduction to the organizational network design problem. The concomitant subproblems (routing and capacity assignment) and the topology design problem formulation are given in Sections 5 and 6. Sections 7 and 8 present a heuristic solution to generate topologies with desired fault-tolerance properties. An example of network design is given in Section 9, and the paper concludes with summary and future extensions in Section 10.

2. Motivation

The changing patterns of potential threats and conflicts in today's world, together with advances in networked communications and computation, necessitate a new approach to the design of organizational structures. The volume of information and complexity of operations require that the information acquisition, processing and decision-making functions be heterarchical, distributed and dynamic over teams of decision-making entities (DMs). Hierarchical organization structures, in which the authority to resolve the most frequent types of exceptions is retained by supervising DMs, can function effectively only for routine tasks with little mutual interdependence among tasks. However, if tasks to be performed by the organization are complex, unpredictable, and highly interdependent, the supervising DMs will be overloaded with coordination overhead associated with the processing of frequent exceptions. As part of our normative research on the design of organizations [4,5,6], we developed a 3-phase process to construct hierarchical organizations. Extensive computational experiments have shown that, when a mission consists of complex tasks requiring multi-resource capabilities (phase 1), even the most efficient allocation of resources to DMs (in phase 2) results in dense coordination requirements among the DMs. In these situations, a hierarchical structure obtained in phase 3 will tend to be flat to minimize the coordination delays. Consequently, a superior DM may become overloaded with exception/request/conflict messages (even when the network contention is small). Allowing lateral relationships among lower-level team members can improve team performance, but would not provide sufficient integration when there is a need for constant coordination among DMs. A network structure would provide the needed integration (accounting for local node constraints). In order to operate in a networked structure, it is important that an organization modify its traditional decision-making, coordination and conflict resolution practices.

Because of the increased interdependencies among various cells of a heterarchical organization (e.g., ISR cell and Strike cell), coordination cannot be engineered, controlled or managed hierarchically. This heightens the need for fine-grained coordination across the increasingly autonomous cells. For example, the individual cells may develop their individual plans concurrently. In concurrent planning, the various cells engage in an ongoing mutual monitoring to resolve conflicting subplans, exploit potential parallelism in task activities, and increase speed of command and the probability of mission success. Since mission planning is subject to deliberation and to modifications across cells, authority is no longer delegated vertically, but rather emerges laterally [8].

In this paper, we extend our three-phase design process to synthesize optimal network-centric heterarchical organizational structures. We utilize the optimal topological design problem formulation [1] to specify communication structures that facilitate information flows among DMs. In this problem, we are given the geographical locations of a collection of decision-making nodes that need to communicate with each other, and a process matrix giving the input information flow from each node to every other node. This matrix is prescribed by the DM-resource-task allocation from Phases 1 and 2 of our design process [4,5,6]. The solution to the problem is a *topology of communication* *network* to service the traffic demands of DMs. This includes the location of nodes, the choice of communication links, and the capacity of each link. The solution is subject to reliability constraints (i.e., fault-tolerance requirements) to guarantee the integrity of organization's communication in the face of a number of link and node failures. The second constraint involves quality of service that keeps the average delay per message below a given level (for the specified nominal communication requirements and assuming some type of information routing algorithm). The objective is to minimize a combination of structure cost and coordination costs, while satisfying the reliability and quality of service constraints.

3. The 3-Phase Design Process

Our mission modeling and organizational design methodology allow one to overcome the computational complexity by synthesizing an organizational structure via an iterative solution of a sequence of three smaller and well-defined optimization sub-problems [4,5]. The three phases of our design process solve three distinct optimization sub-problems:

Phase I (*Scheduling Phase*): The first phase of our design process determines the task-asset allocation and task sequencing that optimize mission objectives (e.g., mission completion time, accuracy, workload, resource utilization, asset coordination, etc.), taking into account task precedence constraints and synchronization delays, task resource requirements, resource capabilities, as well as geographical and other task transition constraints. The generated task-asset allocation schedule specifies the workload of each resource. In addition, for every mission task, the first phase of the algorithm delineates a set of non-redundant resource packages capable of jointly processing a task. This information is later used for iterative refinement of the design, and, if necessary, for on-line strategy adjustments.

Phase II (*Clustering Phase*): In this phase, we combine assets into non-intersecting groups, to match the operational expertise and workload threshold constraints of available DMs, and assign each group to an individual DM to define the DM-resource allocation. Thus, the second phase delineates the DM-asset-task allocation schedule and, consequently, the individual operational workload of each DM.

Phase III (*Structural Optimization Phase*): Finally, Phase III completes the design by specifying a communication structure and a decision hierarchy to optimize the responsibility distribution and inter-DM control coordination, as well as to balance the control workload among DMs with varying expertise.

In this paper, we propose to modify the Phase III to design networked organizations to satisfy the communication requirements among DMs.

3.1. Output Variables of Phases I and II

The outputs of Phases I and II of our design process are the following:

Asset-to-task allocation:

$$y_{ij} = \begin{cases} 1, \text{ if asset } P_j \text{ is assigned to task } T_i \\ 0, \text{ otherwise} \end{cases}$$

Asset-DM allocation:

$$a_{mj} = \begin{cases} 1, \text{ if asset } P_j \text{ is allocated to } DM_m \\ 0, \text{ otherwise} \end{cases}$$

DM-task allocation:

$$u_{mi} = \begin{cases} 1, \text{if } DM_m \text{ is assigned to task } T_\mathrm{i} \\ 0, \text{otherwise} \end{cases}$$
$$= \begin{cases} 1, \text{if } \exists \text{ asset } P_j \text{ such that } a_{mj} = 1, y_{ij} = 1 \\ 0, \text{otherwise} \end{cases}$$

Timing variables:

t_i = time to process task T_i

s_i = start time of processing task T_i

$e_i = s_i + t_i$ = end time of processing task T_i

$\hat{T}$ = finish time of the mission

3.2. Communication

The communication among DMs in an organization is due to two main reasons:

(a) synchronization of assets and coordination due to simultaneous task processing; and

(b) information flow between dependent tasks.

The first type of communication arises whenever two or more DMs are assigned to the same task. The second is due to the information flow between different tasks having precedence constraints; information flow occurs whenever these tasks are assigned to different DMs (this communication is 0 when the tasks are assigned to the same DM). Therefore, we can formally define the communication requirements as follows.

A. Simultaneous Task Processing

This type of communication starts when the task is detected, and could be decomposed into the following stages:

(*i*) asset allocation/request,

(*ii*) asset synchronization, and

(*iii*) communication during task execution.

Without loss of generality in the following, we consider only the third stage of communication. The methodology developed in our work could be easily extended to include all the above communication stages.

We assume that DMs assigned to the same task T_i must continuously communicate during its execution (that is, from time s_i to time e_i) with a rate of r_i units/sec. This type of communication is bi-directional. During a time interval $[0,t]$, the number of units of information communicated between DM_k and DM_m due to simultaneous task processing is given by:

$$F^S_{k,m}(t) = \sum_{i=1}^{N} u_{k,i} u_{m,i} r_i g_i(t)\,, \qquad (1)$$

where N is the number of tasks in the mission, and

$$\begin{aligned} g_i(t) &= \begin{cases} 0, & \text{if } t \le s_i \\ t - s_i, & \text{if } s_i < t \le e_i \\ t_i & \text{otherwise} \end{cases}, \\ &= (t - s_i)U(t - s_i) - (t - t_i - s_i)U(t - e_i) \end{aligned}$$

where $U(t) = \begin{cases} 0, & \text{if } t < 0 \\ 1, & \text{otherwise} \end{cases}$.

B. Inter-task Information Flow

We assume that $f_{i,j}$ units of information must be communicated between DMs assigned to tasks T_i and T_j (when tasks are assigned to the same DM – no communication is needed). This information is required between tasks in the task precedence graph (so that $f_{i,j} > 0$ only if T_i must be executed before T_j), and is attributed to the input-output information needed for task processing. The information arrives as a single packet, and this communication is therefore discrete. The time of arrival of this information is the finish time e_i of task T_i. This type of communication is one-directional. Therefore, the number of units of information communicated between DM_k and DM_m, due to inter-task information flow, in a time interval $[0,t]$ is given by:

$$F^I_{k,m}(t) = \sum_{i=1}^{N} \sum_{j=1}^{N} u_{k,i} u_{m,j} f_{i,j} U(t - e_i)\,. \qquad (2)$$

C. DM-DM Communication Requirements

The total amount of communication between DM_k and DM_m in a time interval $[0,t]$ is computed via

$$F_{k,m}(t) = F^S_{k,m}(t) + F^I_{k,m}(t)\,. \qquad (3)$$

Therefore, the average rate of arrival of information (units/sec) from DM_k to DM_m during the mission (in the time interval $[0,\hat{T}]$) is given by

$$R_{k,m} = \frac{F_{k,m}(\hat{T})}{\hat{T}}\,. \qquad (4)$$

4. Organizational Network Design Problem

Given a collection of DM nodes, and the demands for communication among DMs in the organization (equation (4)), we need to specify a communication network topology structure that services these demands at minimum cost while meeting certain performance requirements. The design objectives are:

- Minimize the average delay per packet;
- Guarantee the integrity of organization's communication in the face of a number of link and node failures, subject to reliability constraints.

The network topology is defined via assignment of capacities to the network links among DMs and specifying the information routing through this network. This assignment is subject to constraints on the cost of creating the network.

One of the solutions to this problem is to decouple the organization topology design into two sub-problems:

(i) Subproblem 1: optimal information routing.

(ii) Subproblem 2: capacity assignment.

Although these 2 sub-problems are inter-dependent, they can be separable under some conditions. For example, suppose that capacity assignment for DM-DM network is fixed. Then, the objective of optimal routing is to find the optimal paths for information flow to minimize the average packet (information) delay. If the paths for information flows in the network are known, solving the capacity assignment problem enable us to achieve the same objective. We will discuss these 2 sub-problems in detail in Section 5, and present a heuristic method to construct an organization networked structure.

4.1. Network Architecture

The DM-DM communication network is defined as a 2-layer architecture (see Fig. 1):

Layer 1: Information Flow Architecture. This layer specifies the information flow requirements among DMs according to DM-task allocation and processing. This layer includes DM-task processing model.

Layer 2: Routing Architecture. This layer provides services to carry out the information flow among DMs identified in layer 1. This layer represents the physical communication network.

If we know the pattern of required information flows in the information flow architecture, we can represent the concomitant traffic flow in the communication network in the routing architecture. The overall delay is the sum of delays in both architectures, as shown in Fig. 1.

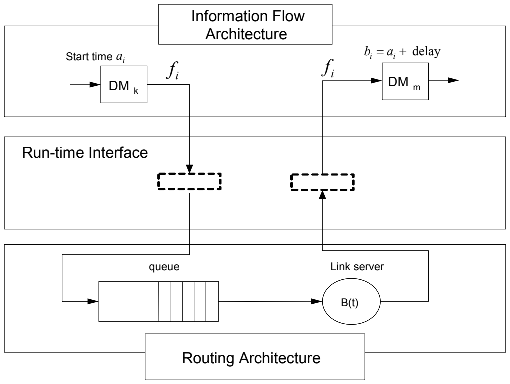

Figure 1. 2-layer structure of information flow among DMs

Our approach is to represent the communication requirements of each DM and the contention for these demands via an embedded link in a single integrated model. This model is based on M/M/1 queuing delay model, with information arrival rate from DM_k to DM_m equal to $R_{k,m}$ units/sec. However, this is only an approximation of the real communication requirements, since the amount of information in DM-DM network during a mission which is dynamic does not reach a steady state (mission duration is finite).

4.2. Delay Model

The routing of information $R_{k,m}$ is found by distributing the flows among the paths from DM_k to DM_m. That is, we need to specify x_p ($x_p \geq 0$) = the flow to be sent through path $p \in P_{(k,m)}$ in the DM-DM communication network, where $P_{(k,m)}$ is the set of all paths from DM_k to DM_m. Hence, the path flows must satisfy the conservation constraints:

$$R_{k,m} = \sum_{p \in P_{(k,m)}} x_p, \forall k,m. \tag{5}$$

For the M/M/1 model, the average amount of information (units) awaiting at the link is given by: $n = \frac{\lambda}{C-\lambda}$, where λ is the information arrival rate (units/sec), and C (units/sec) is the capacity of the link. In our case, we can use the Kleinrock's independence assumption to assume that each link in the network behaves like an M/M/1 queue, regardless of interactions of its flow with the flows on other links [1]. Hence, we can calculate the average number of information units waiting on a link $<k,m>$ as $n_{k,m} = \frac{\lambda_{k,m}}{C_{k,m} - \lambda_{k,m}}$, where $C_{k,m}$ is the capacity of a link $<k,m>$, and $\lambda_{k,m}$ is the arrival rate of information on the link. The rate $\lambda_{k,m}$ is calculated as an aggregated rate of information passing through this link according to the routing of information flow among the DMs:

$$\lambda_{k,m} = \sum_{\substack{\text{all paths } p \\ \text{containing } (k,m)}} x_p \; . \tag{6}$$

As a result, the average number of units of information waiting in the network is equal to $\sum_{k,m=1}^{D} n_{k,m}$, where D is the number of DMs. Since the average arrival of information in the network is $\gamma = \sum_p x_p = \sum_{k,m=1}^{D} R_{k,m}$, we can use the Little's theorem to find the average delay per unit of information:

$$T_D = \frac{1}{\gamma} \sum_{k,m=1}^{D} \frac{\lambda_{k,m}}{C_{k,m} - \lambda_{k,m}}. \tag{7}$$

4.3. Network Cost

Given the price $p_{k,m}$ per unit capacity of the link between DM_k and DM_m, the network construction cost is given by

$$\sum_{k,m=1}^{D} p_{k,m} C_{k,m} \,. \tag{8}$$

5. Optimal Information Routing Problem

5.1. Problem Formulation

Given a topology of DM-DM communication network (that is, the capacities $\{C_{k,m}\}$ are known), the optimal routing problem is formulated in terms of the unknown path flows $\{x_p \mid p \in P_{(k,m)}; k,m = 1,...,D\}$ to minimize the average delay per unit of information in the network (equation (7)). Due to the fact that the average information arrival rate in the network γ is independent of information flow routing and topology, the problem becomes [1]:

$$\begin{aligned} &\min \sum_{k,m=1}^{D} \frac{\lambda_{k,m}}{C_{k,m} - \lambda_{k,m}} \\ &\text{subject to} \begin{cases} \sum\limits_{p \in P_{(k,m)}} x_p = R_{k,m}, \forall (k,m) \\ x_p \geq 0, p \in P_{(k,m)}, \forall (k,m) \end{cases} \end{aligned} \tag{9}$$

The main limitation of the above problem formulation is the fact that the objective function (average delay per unit of information) is insensitive to the undesirable behaviors associated with high variance, and with correlations of inter-arrival times of information and transmission times. The problem is that delay on a link depends on the second and higher moments of the arrival process, but the objective function of (9) reflects the dependence on just the first moment.

Another approach is to optimize the total utilization of the network:

$$\begin{aligned} &\min \sum_{k,m=1}^{D} \frac{\lambda_{k,m}}{C_{k,m}} \\ &\text{subject to} \begin{cases} \sum\limits_{p \in P_{(k,m)}} x_p = R_{k,m}, \forall (k,m) \\ x_p \geq 0, p \in P_{(k,m)}, \forall (k,m) \end{cases} \end{aligned} \tag{10}$$

5.2. Solution Approaches

The problem characterization [1] leads to the following conclusions:

- *Optimal path flow is positive only on paths with a minimum first derivative length* (hence, routing is done through the shortest paths with length equal to the first derivative of the objective function).
- *The optimal paths between two DMs among which the input flow* $R_{k,m}$ *is split must have* ***equal*** *lengths.*

The problems proposed in (9)-(10) could be solved using several optimization methods [1], including feasible directions, Frank Wolfe (flow deviation) method, and projection methods.

6. Network Design Problem Formulation

The problem of optimal capacity assignment is formulated in terms of both the unknown link flows (determined by path flows $\{x_p \mid p \in P_{(k,m)}; k,m = 1,...,D\}$) and link capacities $\{C_{k,m}\}$ to minimize the network construction cost (equation (8)) subject to a constraint that average delay per unit of information does not exceed a specified threshold. The problem becomes:

$$\begin{aligned} &\min \sum_{(k,m)} p_{k,m} C_{k,m} \\ &\text{subject to} \begin{cases} \dfrac{1}{\gamma} \sum\limits_{(k,m)} \dfrac{\lambda_{k,m}}{C_{k,m} - \lambda_{k,m}} \leq \hat{T}_D \,, \\ C_{k,m} \geq 0, \text{ for } \forall (k,m) \end{cases} \end{aligned} \tag{11}$$

where $\lambda_{k,m} = \sum\limits_{\substack{\text{all paths } p \\ \text{containing } (k,m)}} x_p$.

6.1. Capacity Assignment for Fixed Information Flow Routing

When the path flows in a communication network are known, the rate of information flow $\lambda_{k,m}$ on each link is determined via equation (6). Using Lagrangian relaxation techniques, the optimal solution of (11) can be explicitly written as

$$C_{k,m} = \lambda_{k,m} \left(1 + \frac{1}{\hat{T}_D \gamma} \frac{\sum\limits_{(r,u)} \sqrt{p_{r,u} \lambda_{r,u}}}{\sqrt{\lambda_{k,m} p_{k,m}}} \right). \tag{12}$$

Hence, the optimal network design cost is equal to

$$\sum_{(k,m)} p_{k,m} \lambda_{k,m} + \frac{1}{\hat{T}_D \gamma} \left(\sum_{(k,m)} \sqrt{p_{k,m} \lambda_{k,m}} \right)^2 . \tag{13}$$

6.2. Network Design Solution

The problem posed in (11) could be solved by first optimizing (13) with respect to link flow rates $\{\lambda_{k,m}\}$, and then finding the optimal capacities using equation (12). The problem is that optimal cost (13) has many local minima (with a tendency for many of the flows and capacities to be = 0). The resulting network tends to have low connectivity (few links with large capacities) and may violate the reliability constraints. Given the fact that there are many local minima and that the resulting solution may have reliability problems, finding the optimal solution to this problem is intractable.

7. Heuristic Solution to Network Design

We approach the problem of constructing a networked architecture by finding a topology with specified reliability characteristics. Such a solution can be found iteratively by generating new trial topologies and checking for the termination criteria. We assume that:

- The DM nodes of the network and input traffic flows for all pairs of nodes are known.
- An optimal routing model has been adopted that determines the flows $\lambda_{k,m} = \sum_{\substack{\text{all paths } p \\ \text{containing } (k,m)}} x_p$ of all links given all link capacities (Section 5).
- The delay constraint must be met: $\frac{1}{\gamma}\sum_{(k,m)} \frac{\lambda_{k,m}}{C_{k,m} - \lambda_{k,m}} \le \hat{T}_D$.
- The reliability constraint must be met (see Section 8).

The generated feasible topologies are ranked according to their cost (equation (8)). The heuristic algorithm proceeds as follows ([1]; see Fig. 2):

Initialize: *current best topology*, and a *trial topology*

Step 1. (*Assign Flows*): Calculate link flows $\lambda_{k,m} = \sum_{\substack{\text{all paths } p \\ \text{containing } (k,m)}} x_p$ using optimal routing problem (Section 5).

Step 2. (*Check Delays*): Evaluate the average delay per packet $T_D = \frac{1}{\gamma}\sum_{(k,m)} \frac{\lambda_{k,m}}{C_{k,m} - \lambda_{k,m}}$ for trial topology.

if $T_D \le \hat{T}_D$, **then** go to step 3;

else go to step 5 **end if**

Step 3. (*Check Reliability*): Check reliability. If constraints are not met – go to step 5; else – go to step 4.

Step 4. (*Check for Cost Improvement*): If the cost of trial topology is less than the cost of the current best topology, replace the current best topology with the trial topology.

Step 5. (*Generate New Trial Topology*): Use some heuristic to change one or more capacities of the current best topology, obtaining the trial topology that has not been considered before.

8. Network Reliability

When finding a network that accommodates the information flow requirements, we may wish to satisfy certain reliability constraints; this is especially useful in uncertain environments. For example, failures of DMs or DM-DM links must not prevent the flow of information between organizational nodes. Also, due to a possibility of contention on a specific path chosen for information flow transfer, we may wish to design a network that would allow alternative paths to be chosen for routing the flows.

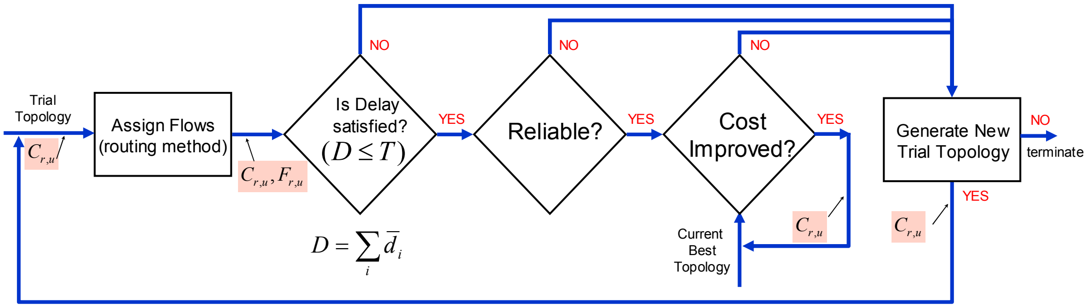

Figure 2. Heuristic algorithm for topological design problem

The reliability criterion of *k*-connectivity, widely used for homogeneous networks, is not applicable in our case since we need to rank the actual paths between the nodes. As stated earlier, the optimal information flow routing procedure sends the flow along paths with minimal first derivative lengths. Therefore, the existence of alternative paths with first derivative length close to the optimal one for every communicating node pair is desired.

Let x be a vector of all path flows: $x=[\ldots,x_p,\ldots]$, for $p\in P_{(k,m)};k,m=1,\ldots,D$ (the length of this vector is equal to the number of all paths in the network). Then the cost function of problem (9) is expressed as follows:

$$d(x)=\sum_{(k,m)} d_{k,m}\left[\sum_{\substack{\text{all paths } p\\ \text{containing link } (k,m)}} x_p\right], \qquad (14)$$

where $d_{k,m}(y)=\dfrac{y}{C_{k,m}-y}$. The first derivative of this function with respect to the flow on a path p is given by:

$$\frac{\partial d(x)}{\partial x_p}=\sum_{\substack{\text{all links } (k,m)\\ \text{on path } p}} d'_{k,m}\,.$$

The first derivatives $d'_{k,m}$ are evaluated at the flows corresponding to x. If $x^*=\{x_p{}^*\}$ is the current optimal flow in the network, then for any DM pair (k,m), we have:

$$x_p{}^*>0\Rightarrow\frac{\partial d(x^*)}{\partial x_p}=\min_{p'\in P_{(k,m)}}\frac{\partial d(x^*)}{\partial x_{p'}}. \qquad (15)$$

Consequently, for a given DM-DM communication network with capacities $C_{k,m}$ and path flows $\lambda_{k,m}$, the reliability of flows for each DM node pair (k,m) is computed as follows:

Step 1. Construct the network with the same nodes, and link lengths defined as $d'_{k,m}(\lambda_{k,m})$ (which is equal to $\dfrac{C_{k,m}}{(C_{k,m}-\lambda_{k,m})^2}$ for the model of problem (9)).

Step 2. Find K shortest paths between DM_k and DM_m: $\{p_1,\ldots,p_K\}$, with p_1 being the shortest path.

Step 3. If $l(p_i)$ indicates the length of path p_i (in terms of network defined in step 1), then the reliability condition for DM_k and DM_m is satisfied if $\forall i=2,\ldots,K: l(p_i)-l(p_1)\le L$, where L is a specified threshold.

The algorithm due to [2] can find the K shortest paths between two nodes in a network of n nodes and m edges in $O(K+n\log n+m)$ time (and find the K shortest paths between a given source and every other node in the graph in $O(K+n\log n+m)$ time).

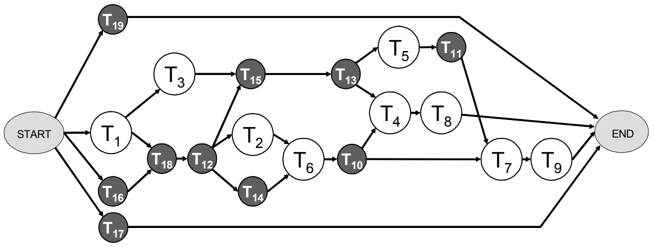

Figure 3. Example of task precedence graph

Table I. Task statistics and task-DM assignment

ID	Task Name	Start Time	Finish Time	Duration	Task-DM assignment				
					DM1	DM2	DM3	DM4	DM5
1	**Take Hill**	48.3755	58.3555	9.98	0	1	0	0	1
2	**Take N.Beach**	94.0881	108.5881	14.5	0	0	0	0	1
3	**Take S.Beach**	76.1151	89.8151	13.7	1	0	0	0	0
4	**Defend N.Zone**	173.296	179.596	6.3	1	0	0	1	0
5	**Defend S.Zone**	195.962	201.162	5.2	1	1	0	0	0
6	**Advance N.Road**	131.442	136.842	5.4	1	0	0	1	0
7	**Advance S.Road**	250.809	262.409	11.6	0	0	0	1	1
8	**Take SEAPORT**	262.41	267.51	5.1	1	0	0	0	1
9	**Take AIRPORT**	179.611	187.911	8.3	0	1	0	0	1
10	**Random Task 10**	152.841	164.141	11.3	0	1	0	1	0
11	**Random Task 11**	237.755	250.855	13.1	0	1	1	0	0
12	**Random Task 12**	87.0209	94.1209	7.1	0	1	1	0	0
13	**Random Task 13**	135.723	149.323	13.6	0	1	1	0	0
14	**Random Task 14**	120.59	131.39	10.8	0	1	1	0	0
15	**Random Task 15**	101.251	112.451	11.2	0	1	0	0	0
16	**Random Task 16**	15.4029	28.4029	13	0	1	1	1	0
17	**Random Task 17**	52.4432	59.5432	7.1	1	0	1	1	0
18	**Random Task 18**	65.7143	76.1143	10.4	0	1	0	0	0
19	**Random Task 19**	37.3962	50.0962	12.7	0	1	0	1	0

9. Example of Network Design Problem

In this section, we consider an illustrative example of designing an organization to execute a mission scenario (consisting of 19 tasks) depicted in Fig. 3 (see [6] for complete details of the scenario and organizational structures). The organization consists of 5 decision-makers, and has 20 assets available for task execution. In phases I and II (scheduling and asset clustering) of the 3-phase design process [4,5], we find the DM-asset-task allocation as depicted in the Gantt-Chart of Fig. 4 and in Table I.

Figure 4. Example Gantt-Chart

Assume for simplicity that cost of a unit of capacity $p_{k,m} = 1$ for every link, and that the rate of communication for simultaneous task processing is constant and equal to $r_i = 1$ units/sec for all mission tasks. We also assume that the amount of information flow between any two tasks connected in the task precedence graph is equal to 5 units/sec. Therefore, the resulting amount of information flow from DM_k and DM_m due to simultaneous task processing is equal to $F^S_{k,m}(\hat{T}) = \sum_{i=1}^{N} u_{k,i} u_{m,i} t_i$, and the resulting amount of information flow due to inter-task precedence constraints is $F^I_{k,m}(\hat{T}) = 5 \cdot \sum_{i=1}^{N} \sum_{j=1}^{N} u_{k,i} u_{m,j} p_{i,j}$, where $p_{i,j} = 1$ if and only if task T_i is a predecessor of task T_j.

Table II. DM-DM communications

Communication due to simultaneous task processing: $\left[F^S_{k,m}(\hat{T})\right]$

	DM1	DM2	DM3	DM4	DM5
DM1	0	5.2	7.1	18.8	5.1
DM2	5.2	0	57.59	37	18.28
DM3	7.1	57.59	0	20.1	0
DM4	18.8	37	20.1	0	11.6
DM5	5.1	18.28	0	11.6	0

Communication due to inter-task information flow: $\left[F^I_{k,m}(\hat{T})\right]$

	DM1	DM2	DM3	DM4	DM5
DM1	0	15	5	5	5
DM2	20	0	20	25	15
DM3	15	20	0	15	10
DM4	10	15	0	0	15
DM5	10	10	0	5	0

The volumes of DM-DM communication $\left[F^S_{k,m}(\hat{T})\right]$ and $\left[F^I_{k,m}(\hat{T})\right]$ are shown in Table II, and the matrix of total communication rates $\left[R_{k,m}\right]$ among DMs is shown in Table III.

Table III. Total DM-DM communication requirement rates

	DM1	DM2	DM3	DM4	DM5
DM1	0	0.075511	0.045232	0.088969	0.037756
DM2	0.094202	0	0.290045	0.231767	0.124407
DM3	0.082614	0.290045	0	0.13121	0.037382
DM4	0.10766	0.194385	0.075137	0	0.099436
DM5	0.056446	0.105716	0	0.062054	0

9.1. Hierarchical Structure

The hierarchical structure obtained using Phase III of our design process produces the tree depicted in Fig. 5. Since there exists a unique path between any two nodes in a tree, the link rates $[\lambda_{k,m}]$ (shown as weights on links in Fig. 5) can be calculated explicitly. The total information rate in the network is $\gamma = 2.23$. As a result, the optimal link capacities for this communication structure, assuming an average information delay of 3 sec, are found using equation (12) and are shown in Fig. 6 (assuming bi-directional network). The cost of the network is therefore equal to 5.156 units (equation (8)).

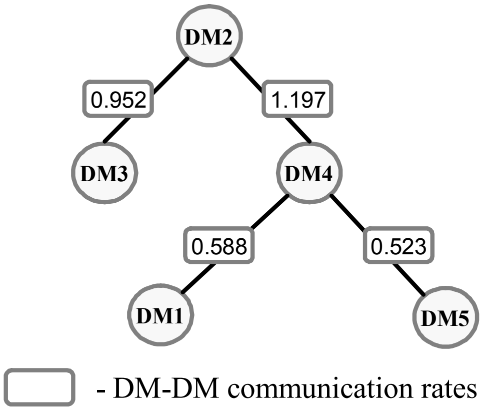

Figure 5. Hierarchical organizational structure and rates

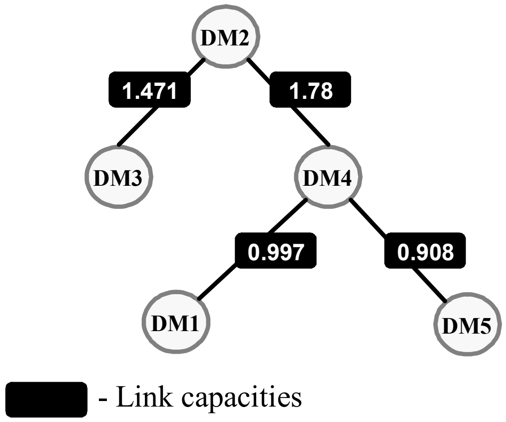

Figure 6. Optimal link capacities for hierarchical structure

Table IV. Fixed Information Routing (Next Node ID)

Current DM	Destination DM				
	DM1	DM2	DM3	DM4	DM5
DM1	-	4	4	4	4
DM2	4	-	3	4	5
DM3	4	2	-	4	2
DM4	1	2	3	-	5
DM5	4	2	2	4	-

9.2. Alternative Structure with Multiple Paths

The hierarchical network structures are very unreliable since the failure of any node or link disconnects the network. In this subsection, we compare the performance of the hierarchical structure with a networked structure which uses a fixed routing. This structure has some reliability properties since alternative paths among nodes are available.

We construct the network by adding links between node pairs $[DM_3 \leftrightarrow DM_4]$ and $[DM_4 \leftrightarrow DM_5]$ to the structure of Fig. 5. The routing of information is fixed as shown in Table IV (the information is routed through a path with minimum number of edges). In this table, a routing is represented as the ID of the node to which the information, having a specific destination node, is sent next from the current node that receives (or originates) this information. This routing results in the communication rates shown in Fig. 7. The optimal capacities for this communication network are found using equation (12) and are shown in Fig. 8 (assuming bi-directional network and a 3-sec average delay). Therefore, the cost of this network is equal to 4.961, which is an improvement over the tree cost of 3.782%.

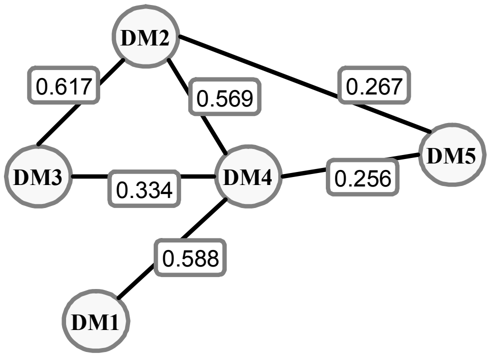

Figure 7. Network organizational structure and rates with fixed routing

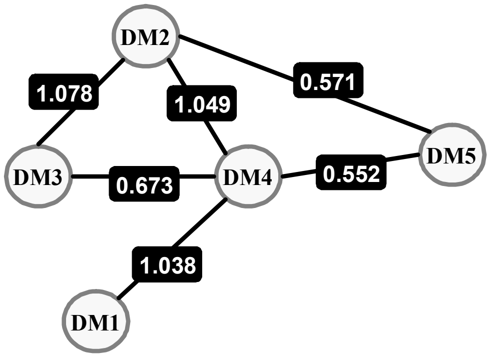

Figure 8. Optimal link capacities for network structure with fixed routing

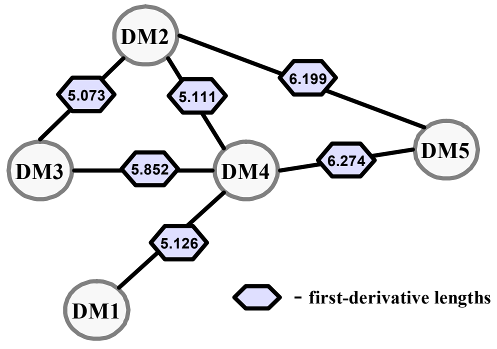

Figure 9. First derivative length network

Finding the first derivative lengths for $d_{k,m}(y)$, we obtain the networks in Fig. 9. It can be easily verified that the routing in Table IV corresponds to the routing through shortest paths in this network. Hence, we conclude that this is an optimal routing and the capacity assignment of Fig. 8 is optimal for this topological structure of the network.

9.3. Fully-Connected and Optimal Networks

The fully-connected network for an example considered in this section has optimal capacities shown in Table V. The information is sent directly between the nodes. The cost of this network is 5.03 units. However, this routing is not optimal considering the shortest paths in first derivative length: the information between DM_3 and DM_5 is not optimally routed.

Table V. Capacities of fully-connected network

	DM1	DM2	DM3	DM4	DM5
DM1	0	0.439245	0.36178	0.486746	0.29501
DM2	0.439245	0	1.0784	0.853257	0.543979
DM3	0.36178	1.0784	0	0.503549	0.163879
DM4	0.486746	0.853257	0.503549	0	0.305747
DM5	0.29501	0.543979	0.163879	0.305747	0

Table VI. Capacities of optimal network

	DM1	DM2	DM3	DM4	DM5
DM1	0	0.431135	0.354742	0.478017	0.288969
DM2	0.431135	0	1.116119	0.840406	0.595712
DM3	0.354742	1.116119	0	0.494607	0
DM4	0.478017	0.840406	0.494607	0	0.299539
DM5	0.288969	0.595712	0	0.299539	0

Just by removing the link $[DM_3 \leftrightarrow DM_5]$ (which carries the smallest communication, and the information through which is not routed according to the shortest derivative length) and routing the information through node DM_2 produces the optimal network with capacities shown in Table VI. The network cost is 4.899. The improvement in cost, compared to the network in Subsection 9.2, is only 1.25%. Given the fact that in realistic applications it is rarely feasible to build and maintain densely-connected networks (the constraints on the maximal number of connections for a node will be violated), we conclude that the network of Subsection 9.2 is satisfactory for our design.

10. Conclusions and Future Extensions

In this paper, we modified our 3-phase design methodology to the problem of designing networked organizational structures based on optimal information routing and topological network design subproblems. The networked architectures outperform traditional hierarchical structures due to a closer match between the multi-layer/multi-link structure of networked organizations and the communication requirements among DM nodes. The hierarchical structures suffer from link and node overheads, and the resulting information delays degrade the performance of such organizations. On the other hand, the networked structures allow minimization of information flow delays and better utilization of networked links while minimizing overheads in the network. Also, networked structures, constructed using reliability constraints, are more robust to failures and environmental changes.

The analytic methods, applications, and measures illustrated in the paper form the basis for current research on organizational design and adaptation for large-scale human-machine systems.

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