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ESTIMATING THE IMPACT OF SYSTEMS ENGINEERS ON SYSTEMS DESIGN PROCESSES

Collopy, Arianne; Greene, Melissa; Adar, Eytan; Papalambros, Panos
University of Michigan, United States of America

Abstract

In this work we develop an understanding of how systems engineers or system integrators can mediate communication channels within a design organization, leading to increased technical success where otherwise no coordination is observed. The models developed here are offered as alternative explanations for observed communication or coordination gaps between design groups working on connected technical subsystems. The results of analysis of simulated organizational network data indicate that systems engineers in mediating roles can improve the probability of technical success as estimated by communication path length within the organizational network. This suggests that roles beyond those directly involved in design tasks should be considered in organizational models used to predict technical system performance.

Keywords: Systems Engineering (SE), Organizational processes, Large-scale engineering systems, Network modelling

Contact:
Arianne Collopy
University of Michigan
Integrative Systems + Design
United States of America
acollopy@umich.edu

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1 INTRODUCTION

Large-scale and complex engineered systems (LaCES) are designed by large, heterogeneous organizations. While this design process can be thought of as a purely technical task, the people that conduct this design work cannot be ignored (McGowan, 2014; de Weck, 2011). While formal systems engineering processes exist to aid the technical design of LaCES through analysis methods and systems management guidelines (Blanchard and Fabrycky, 2011), how systems engineers themselves impact the coordination of work throughout the design organization is not well understood. We build on knowledge of traits of effective individual systems engineers by introducing them into existing measures used to evaluate coordination processes during the design of LaCES. This begins to illustrate how systems engineers may impact coordination processes at a larger scale.

Coordination of design work within an organization requires communication, decision-making, and information processing (Cumming, 2002; Hazelrigg, 1996; Galbraith, 1974). For LaCES in particular, no individual has complete knowledge of the system due to its complexity (Blanchard and Fabrycky, 2011; Bloebaum and McGowan, 2012). Information required to make design decisions about a complex system or subsystem therefore requires leveraging available resources from within the organization: in other words, effective navigation of one's social network (Greene et al, 2016). In practice, this requires effective communication with others, which can be facilitated or hindered by formal organization structures (Herbsleb and Mockus, 2003; Dossick and Neff, 2010; Sosa et al., 2004).

While the design organization is comprised of human actors, the technical system can likewise be represented as a collection of subsystems, their relationships captured in a technical architecture definition. There exists empirical evidence that organizations and the systems they design have similar structures (MacCormack et al, 2012; Colfer and Baldwin, 2016; Le and Panchal, 2012). In the extreme, identical or 'congruent' organization and technical system structures mean that for every technical interaction between subsystems within the designed system, there is a corresponding communication link between the designers or engineers responsible for those subsystems. If perfect congruence between these structures is desired, then it follows that studying the breakdown of the organization will inform understanding of the technical system architecture and its corresponding failure points (Sosa et al., 2004; Cataldo et al., 2006; Gokpinar, 2010).

To determine the degree of congruence, the organizational interactions between engineers involved in the design of a technical system are compared to a representation of the designed system obtained through surveys of system architects, change orders, or modification requests. Points of mismatch are considered potential failure points, either measured as time to issue resolution during design or as the frequency of defects in the product during use. Existing measures of congruence include socio-technical congruence (Cataldo et al., 2006, 2008), affiliation (Sosa, 2008), and coordination deficit (Gokpinar et al., 2010). Based on these measures, effective coordination is based on the presence of direct communication between designers with interdependent tasks.

Here, we build on this previous work and ask what factors may contribute less than full congruence. Past research has focused on understanding what attributes of organizations may lead to observed incongruence, identifying organizational boundaries (Sosa et al., 2004) and indirect interactions between design or engineering groups within the organization (Sosa et al., 2004; Parraguez et al., 2016) as possibilities. We continue this discussion to explore how measures of congruence can be adjusted to include additional members of organization not directly affiliated with a technical task or subsystem, such as systems engineers or system integrators.

Systems engineering is concerned with the entirety of the system, rather than a single discipline or component (Ryschkewitsch et al., 2008). Throughout the design of LaCES, systems engineers are tasked with the system-level design, which includes particular attention to how the subsystem components of a system function together (Blanchard and Fabrycky, 2011). Effective systems engineers are those that are well connected within the organization, are able to communicate well across disciplines, and have a holistic view of the system that enables them to evaluate design trade-offs that affect multiple subsystems (Brooks et al., 2011; Frank, 2006; Williams and Derro, 2008). We choose to focus on systems engineers as their identified skill sets include both a focus on how multiple subsystems interact as well as the ability to work across disciplines, which address previously identified barriers to effective coordination.

Our objective in this work is to illustrate how systems engineers may be included in the analysis of coordination processes based on their ability to work across technical interfaces, and further how their inclusion may change how effective or ineffective processes are characterized. We create a *modified congruence measure* that accounts for the possibilities that (i) communication may be mediated by an intermediate party, whether another design group or a separate systems engineering role within the organization, and (ii) communication may be less critical for standardized technical interfaces or other cases where the technical system is designed to reduce communication requirements across design groups. Our modified congruence measure is implemented on network representations of organization structures generated based on heuristic rules of how engineers and systems engineers communicate within an organization. This work contributes to a discussion of how system engineers can be valuable as part of the design process in practice, as well as how systems engineers may contribute to coordination processes during the design of LaCES.

2 RESEARCH APPROACH

Factors that impact the success of coordination work center on organizational structure, defining roles and their relationship within the organization as well as communication channels between those roles. To evaluate coordination based on communication within organizations, we draw on research on the navigability of social networks, i.e., how people leverage their social networks to transmit or receive information from desired sources, especially those who are outside their immediate acquaintances. Attributes of individuals that may be appropriate to model this navigation process include connectedness (node degree), proximity (location), or profession (organizational role or expertise) (Adamic and Adar, 2005). Networks have also been used to study design processes as a way of connecting multiple system attributes, such as multiple roles in an organization, in a single representation (Parraguez and Maier, 2016). To develop a representation of organization that includes these attributes, we adopt a social network model of organizations to include both attributes of individuals, e.g., their role and location, and their interactions as characterized by the presence of communication. We consider only two attributes of individuals at the outset, but further attributes could be added in the future. The technical system is also represented as a network, where subsystems are joined by technical interfaces.

In this work, we simulate social networks given a generative model that is based on heuristic rules of how engineers and systems engineers communicate within a design organization. To include systems engineers in an analysis of coordination, we develop a modified congruence measure that has positive contribution from the existence of communication between designers that work across a shared technical interface. Rather than a purely binary measure, we base our measure on path length within the organization, or the number of people needed to transfer a message between a given pair of people, based on a fixed communication structure. Negative contributions to congruence come from high values of technical risk. Our modified congruence measure is evaluated for two cases as described in Section 2.3 below.

2.1 Social Network

The geographic distance between designers has been shown to have a significant impact on coordination processes, increasing both the time and effort required to work across subsystems (Herbsleb and Mockus, 2003). To reflect this dependence on distance, a social network to represent the organizational side of this model is generated following Kleinberg’s (2000) 2-dimensional lattice model. This represents that travel only occurs along two dimensions, which we liken to physical paths between individuals in an office setting. This model was selected because it represents distance in two dimensions in a structured environment, assumptions that we believe are reasonable for application to communication within an organization. Kleinberg’s model suggests that long-range connections between people (i.e., those beyond immediate neighbors, or workers more than a few offices away) are expected with a probability inversely proportional to the square of the rectilinear distance between the two nodes. In other words, for an arbitrary pair of nodes u and v, the probability of a link between them is given by

$$P(u \to v) \propto \frac{1}{d(u,v)^2}, \quad (1)$$

where $d(u, v)$ is calculated as the L_1 distance between nodes u and v.

This generative model uses location as the sole criteria for assigning probabilities of communication, i.e., whether or not there is an edge between nodes in the network, with the locations of individuals (nodes) defined by the lattice spacing between adjacent people h. We set the proportionality constant that determines the probability of communication within the lattice to h, therefore the probability of a link with a direct neighbour is $1/h$. Nodes further away have a link probability of $h/d(u,v)^2$ with this scaling. Note also that $P(u \to v) = P(v \to u)$, meaning that the probability of any directed edge is equal to the probability of the reverse edge. A directed edge will not necessarily be generated in both directions, but in this study we take the presence of any directed edge(s) and convert them to an undirected edge.

The N nodes in this network are assumed to be people with the same type of role, e.g., engineer or designer directly responsible for some technical task or subsystem. An additional N_S nodes represent a second role of systems engineers or integrators. Based on the findings that systems engineers can work effectively across disciplines, we give these individuals an equal probability of communication with the engineers and designers within the lattice network, equal to $1/\sqrt{N}$. This probability indicates that systems engineers will have on average $\sqrt{N}$ connections with engineers in the organization; in a group of nine engineers we expect any given systems engineer will communicate with three of them. We select the expected value of $\sqrt{N}$ connections as it represents a focus on a set of subsystems within the organization, and not the entire organization. As the size of the technical system and the affiliated organization increases, the fraction of subsystems addressed by a single systems engineer decreases. This is reasonable given the typical increase in complexity as these systems increase in size and interconnectedness (Bloebaum and McGowan, 2012).

For the rest of this paper, we refer to these two roles as designers and systems engineers, respectively. An example network with N = 9 designers (yellow) and N_S = 2 systems engineers (blue) as generated by this process is shown in Figure 1. In this network, there is a 25% chance of a communication link between any pair of designers and a 33% chance of a communication link between each systems engineer and each designer.

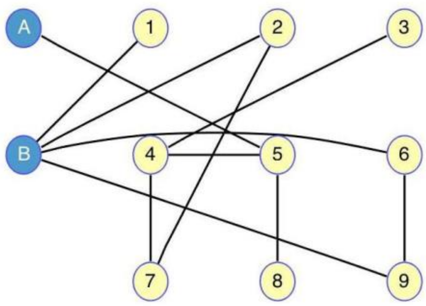

Figure 1. Sample generated network, where h = 5 meters, N = 9, and N_S = 2

2.2 Technical Network

To model the corresponding technical network, we assume a network of size N with maximum density. This represents N technical subsystems where each subsystem has some kind of interface with every other subsystem. The technical system is characterized only by its interface characteristics, i.e. the edge properties of the technical network. We assign the interfaces between technical subsystems a value from 0 to 1 indicating the level of technical risk, ρ, associated with that interface. We do not consider here the variation of technical subsystem attributes or interface attributes other than risk, assuming for the case of this work that these attributes contribute to an estimation of technical risk.

2.3 Modified Congruence Measure

We assume a one-to-one mapping between engineers in the organizational network and subsystems in the technical network. These assumptions then give two cases of coordination between any two pairs of nodes, or dyad pair, as illustrated in Figure 2. The first is a case of full congruence, where there is direct communication between engineers in the organization and a direct link between the corresponding pair of technical subsystems. The second is an intermediate case between full and zero congruence where other designers or systems engineers mediate the lack of direct communication between people designated A1 and B1, for example by communicating with both people even though they do not communicate with each other. This allowance is in contrast to existing analyses of these dyad pairs working across technical interfaces, where direct communication is taken as an indicator of technical success and no direct communication is an indicator of potential technical failure (Cataldo, 2006; Sosa et al., 2004). Other cases such as the lack of an interface between technical subsystems where there is direct communication between the responsible designers are not considered here.

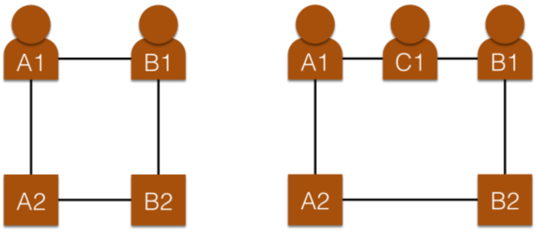

Figure 2. Two cases of coordination illustrated with dyad pairs, where people and technical subsystems are represented as nodes in a simple network. Left: direct communication between people; Right: example of indirect communication between people

To account for this case of mediated communication, we modify the concept of socio-technical congruence originally proposed by Cataldo et al. (2006). This measure looks at every pair of individuals that are working across a technical interface, and reports what percentage of these pairs of individuals directly communicate during design. For example, if socio-technical congruence were calculated for the two cases illustrated in Figure 2, the first case would result in a value of 100% and the second a value of 0%. Recall that we are assuming a maximum density technical network, so that each technical subsystem has an interface with every other technical subsystem. This means that for full socio-technical congruence, a link between every pair of designers is required. To introduce the case of mediated communication as a coordination strategy, though perhaps not equivalent to direct communication, we create a *modified congruence measure* that it is based on the shortest path length ℓ between individuals. The path length between a pair of designers is found by counting the number of people between them based on their communication connections; we choose the shortest of theses. The *local* contribution to the positive component of our modified congruence measure for each pair of nodes is given in Equation 2.

$$MCM_{local+} = \frac{\ell - \mathrm{N}}{1 - \mathrm{N}} \qquad (2)$$

The *overall* positive contribution to the modified congruence measure, MCM_{+}, is then the average of these local values evaluated for every pair of nodes.

We ensure that in edge cases this measure is equivalent to socio-technical congruence by scaling the modified congruence so that a path length of 1 is equivalent to full socio-technical congruence, and that a path length of N is equivalent to zero socio-technical congruence. These choices therefore assume that a more direct communication link is preferable in designing a successful technical interface, and that communication of some kind is required to establish a working technical interface. This could be limiting in that multiple connections through individuals with heterogeneous expertise may be as effective or more effective than a direct link alone (Granovetter, 1973; Parraguez et al., 2016). Extending this model to one that includes attributes of multiple paths is an avenue for future work.

We also introduce a negative contribution to coordination based on the technical risk ρ assigned to an interface. We suggest here that the technical risk assigned to an interface is positively correlated with the difficulty of working across the interface, and therefore reduces the modified congruence measure. We propose a heuristic measure where the highest risk interface is given a 50% chance of coordination success as in Equation 3. This ensures that high-risk interfaces require a high value of MCM_{+}, achieved by close communication between designers, for effective coordination.

$$MCM_{local-} = 0.5\,\rho \qquad (3)$$

For an overall modified congruence measure, MCM, the local negative contribution is subtracted from the local positive contribution, and the resulting values are averaged. We use these two overall measures, MCM_{+} and MCM to evaluate two cases of coordination described below.

2.3.1 Case 1

The first case explored is the allowance of indirect communication within the organization to facilitate coordinated design work. Therefore the first hypothesis to be tested is that increasing N_S, the number of systems engineers in the network, will improve the positive component of the modified congruence measure as given in Equation 2. In this case, we evaluate the organizational network alone using MCM_+, where the overall modified congruence measure is based only on path length within the organization network and disregards any impact of technical risk on coordination. In this model, interactions between designers are more likely if those designers are physically close together. Added systems engineers are randomly assigned connections to designers, which may effectively shortcut paths through the organizational network.

2.3.2 Case 2

The second case we explore is one where technical interfaces vary in their degree of standardization or degree of technical interdependence. We map this to a variation in technical risk, where high standardization is correlated with low technical risk and high interdependence likewise correlated with high technical risk. Because of the balance between the positive contributions to coordination and negative contributions to coordination as outlined above, high risk interfaces are more likely to be successful if close coordination is achieved within the design organization. Therefore the second hypothesis we test is that increasing the number of system integrators to facilitate interactions within the organization has a positive impact on the estimated overall modified congruence measure when technical risk is variable.

3 RESULTS

For each case, a network was generated following the procedure in Section 2.1 with network sizes of $N = 9$, $N = 16$, and $N = 25$. Initially, the grid spacing in the lattice model is set to 5m, representing the physical distance between designers. Note that the proportionality factor in this generative model is the grid spacing h, and therefore we also expect that lower grid spacing will increase the modified congruence measure, and higher grid spacing will decrease the modified congruence measure. The results of this sensitivity analysis are described further in Section 3.3.

3.1 Case 1: Indirect communication

To evaluate the impact of additional systems engineers mediating communication within the organizational network, a series of 100 networks were generated for each network size and for varying numbers of integrators, and results averaged across all iterations. For each set of parameters, the overall positive contribution to the modified congruence measure was averaged across all iterations. As shown in Figure 3, when the number of added nodes representing systems engineers increases, the modified congruence measure increases. This measure is higher in all cases for larger networks because of the corresponding increase in possible communication paths within the organizational network.

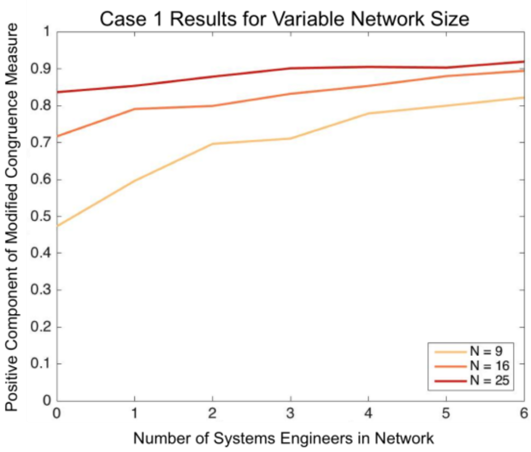

Figure 3. Mean modified congruence measure values for networks of N designers and varying numbers of systems engineers for a lattice spacing of $h = 5$ *meters*

The influence of added systems engineers is less for larger networks, meaning that the modified congruence measure increases less for each added systems engineer. This can be explained by the way the probability of link connection between added N_S scales with N. The probability of a link between a new systems engineer added to the network and one of initial N designers is $1/\sqrt{N}$, therefore each systems engineer node is expected to have a link with 3, 4, or 5 designers respectively for each network size considered here. When the systems engineers have more connections on average, the average path length is reduced for more pairs of designers, raising the positive component of the modified congruence measure. These results are for the addition of individuals in the organization that behave as communication intermediaries, one possible role of systems engineers.

3.2 Case 2: Variable technical risk

For the case of variable technical risk, we consider two scenarios. The first is uniformly distributed risk to each interface between technical subsystem pairs, i.e., $\rho \sim U(0, 1)$. The second is normally distributed risk given $\rho \sim N(0.5, 0.0225)$. For each scenario, results were averaged across 100 simulations. The mean value of the modified congruence measure as estimated for a technical system with uniformly distributed risk and a technical system with normally distributed risk is shown in Figure 4.

Both distributions of risk within the technical network show a similar trend as that for Case 1, indicating that more systems engineers show an increase in the modified congruence measure here as well. In contrast, the value of the modified congruence measure when there are no systems engineers and when there are six systems engineers are both lower than in Case 1 where no risk is included.

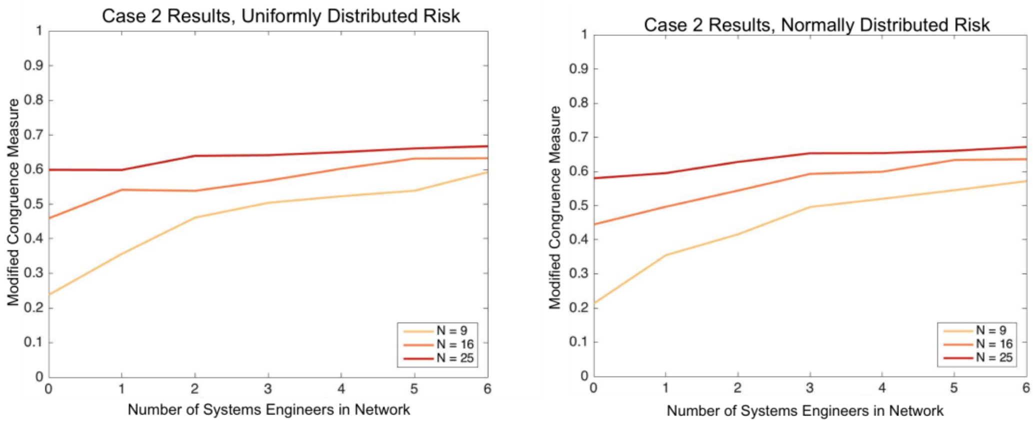

Figure 4. Mean modified congruence measure values assuming uniformly (left) and normally (right) distributed risk variation for networks of N designers, N technical subsystems, and varying numbers of systems engineers for a lattice spacing of h = 5 m

The result for this case also illustrates a dependence of the modified congruence measure on network size as seen in Case 1. The smallest network of 9 designers and 9 technical subsystems appears to be particularly vulnerable to risk without the inclusion of systems engineers. This result can be explained by the fact that the parameters used in the network generation model permit disjoint network components, meaning that a systems engineer is required to bridge these isolated groups. This is particularly true for disjoint components with only a single person that is isolated from the rest of the organization.

Uniformly and normally distributed risk give roughly the same results. A uniform distribution of risk is expected to show elevated frequencies of both low risk and high risk technical edges as compared to normally distributed risk. We might expect that systems engineers have a higher impact in the case of elevated high-risk interfaces, where they can help to reduce the communication path between designers. We may also expect that systems engineers have less impact in the case of elevated low risk interfaces, where there are fewer consequences of a slightly less efficient communication path between designers. Neither of these cases stands out in comparing the results of uniformly and normally distributed technical risk. This may be because the high and low impacts of systems engineers balance each other out, but it is also possible that with the random distribution of both technical risk and link assignment for systems engineers, there is too much variance in these models to observe a strong trend in either case. This is particularly likely for the small network of size N = 9, where there are only 36 edges in the technical network. In this case, the sampled risk values are less likely to be representative of either distribution, making it difficult to conclusively distinguish results.

3.3 Sensitivity Analysis

One important parameter in these results is the lattice spacing, h. The probability of link formation within Kleinberg's 2-D lattice model is set to be proportional to h, meaning that larger spacing between nodes will decrease the number of links within the lattice. The systems engineers in this model are able to connect to designers at all distances with equal probability, suggesting that they will have a greater impact on the modified congruence measure where lattice spacing is large, meaning designers are physically farther apart. Table 1 shows the values of the modified congruence measure for multiple values of h and N_S, for a network of N = 16 designers. These results are based on the assumptions made in Case 1 of no impact from risk.

Table 1. Mean values for modified congruence measure for networks of size N = 16 with lattice spacing h and N_S systems engineers

h	$N_S = 0$	$N_S = 1$	$N_S = 2$	$N_S = 3$	$N_S = 4$	$N_S = 5$	$N_S = 6$
2.5m	0.9193	0.9283	0.9337	0.9352	0.9405	0.9342	0.9380
5m	0.7165	0.7907	0.7989	0.8319	0.8532	0.8798	0.8941
10m	0.2804	0.4145	0.5713	0.6629	0.6974	0.7548	0.7879
20m	0.0781	0.2021	0.3241	0.4493	0.5310	0.6522	0.6685

These results make clear the impact of distance on our modified congruence measure, as it increases when the individuals modeled by this network are physically closer together. These results also indicate that increasing the number of systems engineers in the organizational network has more of an impact when the spacing between designers is larger, as determined by comparing the values in successive columns in Table 1. For example, adding a third systems engineer when the spacing is 10m increases the modified congruence measure by 0.09, while doing the same when the spacing is 5m increases the modified congruence measure by only 0.03. This also suggests that below a certain size network and a certain average spacing between designers, the effect of mediators such as systems engineers is diminished.

Based on the given model of coordination, these results are intuitive as designers and engineers are less likely to connect with each other when they are far apart, and because systems engineers are equally likely to connect to any designer irrespective of distance. Conducting a similar analysis of communication patterns in an actual design organization is the next step to determine whether the effectiveness of communication in designing across technical interfaces is as dependent on distance as this model suggests, or if another model might be more appropriate. An example might be the use of a rank-based model such as that proposed by Liben-Nowell et al. (2005), based on the relative location of nodes rather than absolute location.

4 LIMITATIONS AND FUTURE WORK

The results presented here depend on a number of assumptions, particularly regarding how designers and systems engineers communicate during design, and how technical interfaces are characterized. The probability of communication between designers could be adjusted to include a higher probability of communication with those who have similar technical expertise or a different distribution of communication. The probability of communication between systems engineers and designers could be adjusted in the future to include any biases based on shared previous experience. Communication channels are also assumed to have constant quality, when in reality the ease of communication depends on the message content, the communication medium, and the consistency of mental models held by those communicating (Olson and Olson, 2000; Mortensen, 2014).

We also limit the scope of our discussion here to the question of how systems engineers may be integrated into the existing measure of socio-technical congruence, and what the results of that integration are. This does not make a distinction between different stages of the design process, where different coordination requirements are likely to occur (Parraguez et al., 2015). Considering systems engineers as dynamic actors that contribute to different areas of the organization at different times and in different ways may increase the impact of single systems engineers or integrators, refining the analysis presented here. We acknowledge as well that other roles within the organization may impact coordination processes as well, including technical managers as well as other divisions of the organization such as manufacturing or marketing.

There are two primary ways to extend this work by focusing on (1) the representation of organization structure and technical system architecture, and (2) the development of more robust models of coordination processes. One important difference between simulated network data and the study of an organization is the potential lack of structure in the simulated network that may be present in an actual organization. Here, the attributes of role and location are used to characterize the organizational network, with particular emphasis placed on the importance of representing multiple organizational roles. Depending on the design organization, other descriptors may be more appropriate to accurately represent actual coordination work. Work to refine the model of coordination processes as presented here could include multiple paths for communication rather than the single shortest path described here, path attributes such as the attributes of people encountered along those paths, and structural attributes of the organizational and technical architectures.

5 CONCLUSIONS

In this paper, we have illustrated how systems engineers can be included in evaluation of coordination processes in design organizations. Using a model of technical performance based on communication paths within the design organization and the distribution of risk within the technical system, we were able to test two hypotheses regarding the influence of systems engineers on communication within a design organization. The results of analysis of these networks indicated that systems engineers improve measures of congruence in both cases, for varying network sizes (indicating number of designers and number of technical subsystems given a one-to-one mapping) as well as varying physical distance between members of the design organization.

These results indicate that neglecting members of the organization that are able to mediate between design groups within the organization may result in an inaccurate representation of coordination practices. These results also suggest that efforts of those able to mediate effectively between design groups may mitigate gaps in direct communication between designers. These results come from simulated networks, but similar measures could be used to analyze corresponding data from design organizations to uncover integrator-type roles within the organization as well as understand the impact of systems engineers on the design process of technical systems.

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