ON THE STABILITY OF COORDINATION PATTERNS IN MULTIDISCIPLINARY DESIGN PROJECTS

João Castro[1], Martin Steinert[2] and Warren Seering[1]
(1) Massachusetts Institute of Technology, USA (2) Stanford University

ABSTRACT
Participants in product design and development projects need to interact to coordinate the impacts and dependencies of their work on the product. Based on data from NASA Rocket Design projects we analyze and compare a series of product development projects within the same organization where objectives and team composition differ. We focus on the connections that are made between team members and the nature of the project and relate the two. Findings reveal that similar design problems exihibit similar dependency structures and allow for organizational learning opportunities.

Keywords: Multidisciplinary design, Team communication, Design interdependencies,

1 INTRODUCTION
In this paper we present data from NASA Mission Design Center projects that allow us to compare the stability of established communication patterns across multiple design projects. Projects that address similar design problems show similar communication patterns. Based on this relationship, it is possible for program managers to optimize and support communication connections and to speed up organizational learning.

As a project is conducted, participants may engage other team members in order to solve a mutual dependency or to coordinate around a trade-off. Each participant not only has to execute his tasks but is also responsible for navigating the set of possible interactions with other participants.
When doing this, participants have to prioritize these connections. Not all of them can be addressed due to resource constraints. For very large teams it is unreasonable to expect that a designer will engage with every other single project member in order to verify if there is a dependency and to guarantee agreement. The number of total communication links in a project is given by $n(n-1)/2$ where n is the number of participants in a project.
For any given project, the ability to predict and identify dependencies between different disciplines will allow mangers and project participants to address them. This can have significant impact on project performance and has been the focus of previous studies [1] and [2].
When a team takes on several projects, the observed connections among the participants might be similar or distinct when we compare the projects. A connection that was made in one project may or may not be made in another project. The experience acquired in a previous project may tell whether a specific connection is or is not relevant, what issues were identified and, maybe depending on the nature of the product, if the set of connections are or are not different.
In order to test this, we formulate the following hypothesis:

Hypothesis – The communication channels that are relevant in a project will be the same in a different project if these projects are similar

A test of this hypothesis is described in the following sections. First, we explain the project environment requirements and characteristics that are adequate for this test. Next, we describe how data was collected, treated and set up for analysis. We then detail the results and robustness tests. Finally, we summarize the findings and elaborate on how these results may impact practitioners.

2 RESEARCH SETTING

The objective framed within the hypothesis is to test the similarity between the communication channels established in one project with other projects done by the same organization. This requires a data source where multiple projects have taken place and in which their running conditions are mostly similar. Projects with different scope, budget, schedule, team membership, team size and geographic dispersion among other things can have any one of these factors generating confounding issues into the observations we want to test. While it is almost impossible to control all of them, we obtained a dataset that is adequately strong for these purposes. From this dataset we can extract the differences between projects and a measurement of communication between team members.

2.1 The NASA Mission Design Center

A recent study on socio-technical congruence in design processes collected data at a NASA integrated concurrent engineering mission design center. Part of the collected data was kindly made available for the present study. The original resulting document [3] includes a detailed description of this center, including historical developments and its role within NASA and other affiliated design centers.

Briefly, the NASA Mission Design Center designs spacecraft and mission architecture for Earth-orbiting or planetary missions. This involves the contributions from several disciplines: Attitude Control, Avionics, Communications, Electrical Power, Flight Dynamics, Flight Software, Integration and Test, Launch Vehicles, Mechanical, Mission Operations, Orbital Debris, Parametric Cost, Propulsion, Radiation, Reliability, and Thermal. The design sessions normally involve 20 to 25 people, with one or two representing a discipline, and make up a "full design team working together in the facility throughout the entire design study, which usually lasts about a week". This study looked at 13 different projects in which the team was co-located in one specifically built room with stations for each discipline and the effort required for communication between different disciplines inside this room is negligible. The type of missions the team was asked to design were mostly similar and therefore the "design process [was] somewhat routine" although they did experience some missions that fell out of their "traditional comfort zone". Missions were staffed with a combination of disciplines depending on the design objectives and the people in each position were not always the same.

3 DATA COLLECTION AND ANALYSIS SETUP

The field data was collected by [3] through the use of surveys. These surveys were administered online before and after each mission to each mission participant, and an 80% response rate was achieved.

In order to test our hypothesis we wished to observe two things:

1. The communication channels established between project participants and how important they are, and
2. The differences and similarities between projects

From the survey that was administered to project participants, there was one relevant question for this study. Question number 6 stated:

> "For the current study only, please indicate the importance of direct communication between you, serving in your subsystem role, and each of the other members of the design team. Please use the space below to comment on any particularly interesting or unique design issues discussed with other members of the design team."

The respondent was then asked to report using a four-point Likert scale with the following level values:

> 0 - Unnecessary, 1 - Helpful, 2 - Important, 3 - Essential

Respondents were given a list of all the different functional areas involved in the project in which they participated so they could rate their interactions with the other participants. The differences and similarities between the projects were obtained by analyzing the team constitution. Each project had a team staffed in the required functional areas. Some projects required more or less areas to be staffed depending on the type of mission being designed and so, by looking at how a project was staffed, comparatively to others, we can observe how different they were.

3.1 Analysis environment

The relevant and anonymized collected data was fed into a database system for analysis. The entries in the database's main table included:
- the unique, anonymous identifier of the respondent,
- the functional area to which they belonged,
- the project in which the answer was given,
- the target of their observation and
- the value of their response.

By formulating queries to the database it was possible to quickly obtain answers to questions such as:
- Who did person from functional area X consider 'essential' in project 1?
- How many connections considered 'essential' or 'important' were established in project 6?
- Which functional areas considered functional area Y as 'essential' to their work?
- What is the average number of targets considered as 'essential'?

4 DATA ANALYSIS & RESULTS

A comprehensive analysis on the social and technical constraints of how people interact with others in teams is outside the scope of this study. However, an observation of the 41 individuals who participated in these projects reveals that they typically elect a core group of people that are more important to them. On average, participants select a third of the other functional areas as essential to them (level 3), 39% as useful (level 2) and 28% as only helpful (level 1).

4.1 Measuring Project Similarity

The comparison of different projects was done by analyzing which functional areas were staffed in each project. When representing the array of functions used by projects as a binary vector we can obtain a representation of a project as:

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	0	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	0	1	1	1

Table 1 - Functions used by project

Where function names are reduced to a single letter symbol and a "1" denotes that the function is being used for that mission and a "0" denotes that there is no one in that capacity for that specific mission.

The following table is obtained by representing all of the mission vectors:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
Project 1	1			1		1		1	1	1	1	1		1	1	1	1	1	1	1
Project 2	1		1	1		1		1	1	1	1	1	1	1	1	1	1	1	1	1
Project 3	1		1	1		1		1	1	1	1	1	1	1		1	1	1	1	1
Project 4	1			1	1	1		1	1	1		1	1	1	1	1	1	1	1	1
Project 5			1	1	1	1	1	1	1	1		1	1	1		1	1	1	1	1
Project 6	1		1	1	1	1		1	1	1		1	1	1		1	1	1	1	1
Project 7	1		1	1		1						1						1	1	1
Project 8	1		1	1	1	1		1	1	1		1			1	1		1	1	1
Project 9			1	1		1		1	1	1		1	1	1	1			1	1	1
Project 10	1	1		1				1												1
Project 11	1		1	1		1		1	1	1	1	1	1	1	1	1	1	1	1	1
Project 12	1		1	1		1		1	1	1	1	1	1	1	1	1	1	1	1	1
Project 13	1		1		1	1			1	1		1	1	1	1	1	1		1	1

Table 2 - Functions used by all projects

Comparing two projects - In order to verify how similar two projects are we used their respective functional area vectors. The measure of similarity is calculated by obtaining the ratio of the number of functions commonly used by two projects over the number of all functions used by the pair of projects. This is the same as saying in set logic as the ratio of the intersection over the reunion of functions.
For example, comparing the functional vectors of project 1 and 2:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
Project 1	1	0	0	1	0	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1
Project 2	1	0	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 3 - Comparing the functions of two projects

The only difference between these two projects is the use of functional areas C and M. There are 15 functional areas in common and 17 total functional areas. By the measure defined before, these projects have a similarity measure of 15/17= 0.882

Comparing all the projects - By repeating the measurement of similarity for every pair of projects we get:

	1	2	3	4	5	6	7	8	9	10	11	12	13
1													
2	0.882												
3	0.824	0.941											
4	0.824	0.833	0.778										
5	0.632	0.737	0.778	0.778									
6	0.722	0.833	0.882	0.882	0.882								
7	0.438	0.471	0.500	0.412	0.412	0.500							
8	0.706	0.722	0.667	0.765	0.667	0.765	0.571						
9	0.647	0.765	0.706	0.706	0.706	0.706	0.500	0.688					
10	0.250	0.222	0.235	0.235	0.167	0.235	0.300	0.267	0.200				
11	0.882	1.000	0.941	0.833	0.737	0.833	0.471	0.722	0.765	0.222			
12	0.882	1.000	0.941	0.833	0.737	0.833	0.471	0.722	0.765	0.222	1.000		
13	0.611	0.722	0.667	0.765	0.667	0.765	0.375	0.647	0.588	0.118	0.722	0.722	

Table 4 - Correlation coefficient between functional areas of projects

From the analysis of this table we can verify that projects 2, 11 and 12 have the same functional constitution while other vary in their degree of similarity.

Measuring Communication Importance Similarity

The other comparison between projects is their similarity of importance of communication between functions. In each project, respondents graded their peers in terms of importance of communication. As each participant was responsible for a specific functional area, with this information I can establish a correspondence between the different functions and represent it in a table for each project, such as:

Project X	Functional Area						
Functional Area	A	B	C	D	E	F	…
A							
B							
C							
D							
E							
F							
…							

Table 5 - Example of table for communication importance between functions in a project

Comparing two projects - In order to compare the communication patterns of two projects we take the values in Table 5 and represent them as a line by line sequence, obtaining a vector for the importance of communication for a specific project.
When comparing two projects, if they both don't use a function then it is removed from their representations. With two vectors from two projects and by calculating the correlation coefficient between them, we get a measure of how similar the communication patterns in the two projects were.

Comparing all the projects - By repeating the procedure for every pair of projects, we get the full table of similarity of communication importance:

	1	2	3	4	5	6	7	8	9	10	11	12	13
1													
2	0.557												
3	0.430	0.555											
4	0.529	0.564	0.473										
5	0.375	0.446	0.515	0.621									
6	0.448	0.542	0.575	0.631	0.704								
7	0.438	0.401	0.421	0.372	0.368	0.419							
8	0.247	0.301	0.162	0.399	0.372	0.394	0.296						
9	0.401	0.470	0.240	0.388	0.373	0.335	0.421	0.512					
10	0.181	0.132	0.022	0.056	0.038	0.090	-0.069	0.050	0.114				
11	0.423	0.492	0.421	0.482	0.304	0.324	0.327	0.262	0.395	0.012			
12	0.542	0.556	0.417	0.552	0.414	0.397	0.362	0.349	0.441	0.047	0.605		
13	0.273	0.433	0.322	0.501	0.428	0.396	0.261	0.334	0.229	-0.013	0.372	0.487	

Table 6 - Correlation coefficient between communication importance of projects

From the analysis of this table we can verify that the two projects whose importance of communication between participants most resembled each other were project 5 and project 6 and that the projects 10 and 13 were the two least alike.

Joint plot of project similarity and communication link similarity

We can now compare how these two sets of values, project similarity and communication importance similarity, are related. For example, Project pair 1 and 2, have 0.882 in project functional similarity and 0.557 in the importance of communication channels similarity. Graphically this can be represented as a scatter plot, with each marker representing the values for a given pair of projects. Since we have 13 projects, the total number of possible pairs is n(n-1)/2 = 78.

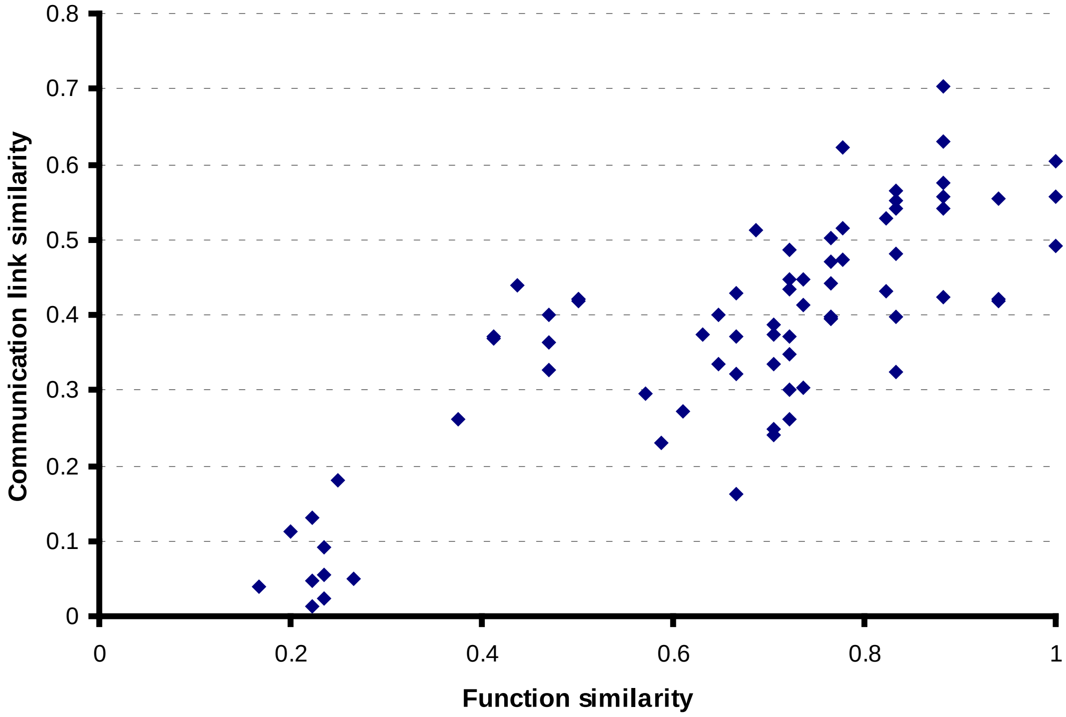

Figure 1 - Relating function similarity and communication importance similarity

From this chart we can immediately observe the correlation between the two measures. Projects that are more similar in their functional domains also exhibit a more similar pattern of importance of communication. The R^2 value of this distribution is 0.6818.

Validity test

One of the threats to the validity of these results is auto-correlation between the two observations.

Auto-correlation can happen when two different measurement methods reflect the same variable. Regarding the measurements being made for these projects, one verifies which functional areas are present in a project while the other measures how important areas in a project regard the other areas in the same project.

The threat of auto-correlation is present since the areas that respond to the second question are the same as those that are present in the project. A functional area that is not present in a project will not provide data on other functional areas.

If, in a reductionist approach, it is considered that all areas communicate with all other areas at the same level of importance then effectively this representation would mirror the functional area data and auto-correlation would be observed. In the actual case, the data collected is much more detailed. Each project participant representing a functional area ranks all other functional areas on a scale. This allows room for differences to emerge between the two types of observations.

Testing auto-correlation

One way to test this auto-correlation is by exploring the solution space of variables. If the importance of communication measurement is constrained, i.e. not independent, from the project similarity measure, then a simulated run of results will also show this.

In each test run and for each functional area we assigned a random importance value to the other functional areas that were present in a project. We followed the values observed earlier in that there is a distribution on the type of connections that are made.

After the connections within each project were established, we computed the similarity value between projects as before. This entire process was repeated ten times, in each run generating a set of random communication importance levels between the functions used by a project and then calculating the similarity values between projects.

This generated (13*12/2) * 10 = 780 values. When plotted together with the observed values we get:

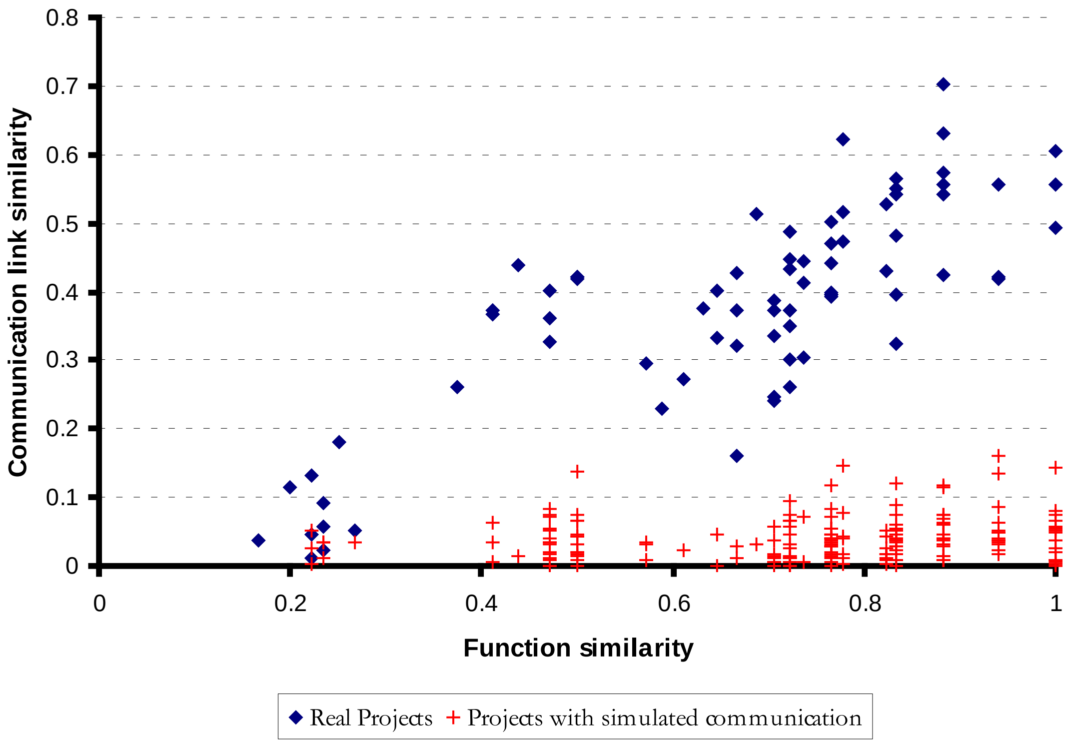

Figure 2 - Function similarity and Communication importance with simulated projects

This test also illustrates the p-value of the observed results. The p-value is very low, meaning that the observations that were made are very unlikely due to a random assignment of values. Graphically this is seen by how distant the observed values are from those generated in the random runs. We may thus conclude that the relationship between communication links similarity and function similarity is not random.

5 CONCLUSION

The hypothesis stated: "The communication channels that are relevant in a project will be the same in a different project if these projects are similar". From these results we can observe that there is a direct correlation between functional similarity and the pattern of important communication channels. It is also observable that this correlation is not simply due to the constitution of the teams. Considering that participants in these projects are free to engage with any other participant, what these results illustrate in terms of team interactions is that similar projects have similar communication channels. When a team starts another project, its participants will mostly interact with the same areas as before given that the new project is similar to the previous one.

6 OTHER CONSIDERATIONS

The efficiency of the team performance wasn't measured, so it isn't possible to analyze a relationship between the connections being made and the success of the project. It may be possible that there are other sets of connection combinations that achieve a similar or better result. Also, several other projects had been conducted before the data was collected and the participants involved in these programs were experienced and familiar with their role, the design process and the roles of other participants. This can explain the stability of the connections. The resulting combinations may be an emergent set of a path-dependent design optimization taken by the teams.

Implications for practitioners

The data collected for this study originated from a specific environment, NASA. The scope of each project was mission planning and no detailed design was pursued. The duration of each project was limited (1 week) and all participants shared a common space for the duration of the project.

Even simple product development projects have durations that are typically longer than those observed and proceed throughout detailed design and verification stages until entering production. Nevertheless, the observed projects focused on the early stage of a mission design. Most of the cost of a product is decided in the early stages of its development [4] so a study that analyzes only this stage is relevant.
With a preponderance of similar connections when projects are similar, product development managers can, when setting up new projects, predict with some probability which connections between participants will be important. If a project manager is able to identify all the important connections between project participants then it is possible to optimize the operating environment of that team. The project manager can assign any of the coordination methods to enable the closely related people to exchange the information they require.
By facilitating and focusing on the communications that are important, and avoiding spending effort on the least relevant, practitioners will be able to improve the quality of their product development. This method presents an approach specifying how to identify those connections based on past project experience.

REFERENCES

[1] Sosa, M.E. et al. 2004. The Misalignment of Product Architecture and Organizational Structure in Complex Product Development. Management Science, 50(12), pp. 1674-1689.
[2] Morelli, M.D. et al. 1995. Predicting technical communication in product development organizations. IEEE Transactions on Engineering Management, 42(3), pp. 215-222.
[3] Avnet, M. 2009. Socio-cognitive Analysis of Engineering Systems Design: Shared Knowledge, Process and Product. MIT - Engineering Systems Division, p. 274.
[4] Ullman, D. 2002. The Mechanical Design Process. McGraw-Hill Science/Engineering/Math.

Contact: João Castro
Email: joaoc@alum.mit.edu

João Castro is a Product Development and Innovation Management professional. He holds a PhD in Engineering Systems from the Massachusetts Institute of Technology. His research interests combine product development, complex systems, teams and end user design. He also teaches Management of Innovation and Entrepreneurship to MBA classes at Universidade Católica in Porto, Portugal.

Martin Steinert is Deputy Director of the Center for Design Research (CDR) and the Hasso Plattner Design Thinking Research Program (HPDTRP) at Stanford University. He holds a PhD in Technology and Innovation Management from the University of Fribourg/Switzerland. His research focuses on the fuzzy front end of innovation with the aim to optimize the intersection between engineering, new product development and the design process.

Warren Seering is Weber-Shaugness Professor of Mechanical Engineering and Professor of Engineering Systems. Professor Seering's research interests include machine dynamics, engineering system design, and product development. His teaching interests center on product development, design and dynamics. He is a Fellow of the ASME. Professor Seering is a member of the American Society of Mechanical Engineers and the Design Society. He holds a PhD from Stanford University.