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# Information Flows in Networked Engineering Design Projects

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**SUMMARY:** Complex engineering design projects need to manage simultaneously multiple information flows across design activities associated with different areas of the design process. Previous research on this area has mostly focused on either analysing the "required information flows" through activity networks at the project level or in studying the social networks that deliver the "actual information flow". In this paper we propose and empirically test a model and method that integrates both social and activity networks into one compact representation, allowing to compare actual and required information flows between design spaces, and to assess the influence that these misalignments could have on the performance of engineering design projects.

Several studies have highlighted the importance of communication in the engineering design process (Eckert et al. 2004; Maier et al. 2009; Littler et al. 1995; Maier et al. 2005) and its impact on project performance (Kratzer 2001; Tushman et al. 1980; Kratzer et al. 2010). One way of modelling communication with the aim of better understanding and supporting the design process are information flows. The information flows can be modelled as expected communications based on known information needs between design activities or actual communication. The first can be described as "required information flows" and the later as "actual information flows".

Models of required information flow describe what are believed to be necessary information exchanges or information dependencies between elements of a system. They include information inputs and outputs between activities of a process (Smith & Eppinger 1997; Steward 1981; Eppinger et al. 1994), information dependencies between components of a product (Sharman & Yassine 2004) or formal organisational structures defining interactions between members of a project. In turn, models of actual information flow try to capture effective interactions between elements of a system. They include ex-post reports about actual information exchanges between activities of a process, reports on actual information exchanges between components of a product or work-related interactions between members of an organisation (Carpenter et al. 2012; Kilduff & Brass 2010; Batallas & Yassine 2006).

The study of misalignments between what is intended (required information flow) and what actually happens (actual information flow) is attractive because it can reveal issues due to mismatches between usually top-down perspectives about required information flow and bottom-up emergent behaviours. Examples of previous research utilising network analysis to study different kinds of misalignments include comparisons between the formal and informal organisation (Kratzer et al. 2008; Allen et al. 2007), misalignments of product architecture and organizational structure (Sosa et al. 2004; Le & Panchal 2012), product architecture and process architecture (Sosa et al. 2012), and process and organisational architecture (Collins et al. 2010; Morelli et al. 1995; Durugbo, Hutabarat, et al. 2011).

This research is part of the last kind of studies, at the intersection between required information flows between activities (described at the project level) and actual information flows between members of a project. Our objective is to identify misalignments between required and actual information flows and test the impact of those misalignments on performance. In order to do so, we propose and empirically test with an industry partner a network model of required and actual information flows in engineering design projects and a method to quantify and compare those flows. The underlying hypothesis is that areas where required information flows exceed the levels of actual information flows are more likely to experience performance problems related with insufficient communication and therefore might require strategic interventions.

Engineering design projects are composed by a large number of activities grouped around areas of development that later need to be integrated to achieve the desired project performance. Although coordination, and in general communication, within each activity group are important for a successful design, coordination complexity tend to be greater between activity groups than within them, this can be explained due to higher social dissimilarities, less cohesion and different design objectives. This paper uses the concept of "Design Spaces" to describe these groups of activities as social processes in a collective space where design engineers define, evaluate and/or manage the design object(s) associated with specific areas of development in the project. Each design space is associated with a collection of design activities, people and context (space, time, objective, resources, etc.) and are characterised using a network that describes an open system with information inputs and outputs. In this way design spaces allow to situate design and model the information flows at the level that is most important for system integration and coordination.

The motivation behind this research is derived from observed industrial needs and identified literature gaps. From the industrial practice and previous research we noticed that engineering design companies frequently encounter communication problems at the interfaces of different processes, teams or groups of activities (Maier et al. 2012; Clarkson & Eckert 2005, p.20; Bucciarelli 1988; Austin et al. 2001). This happens despite of often counting with a project level view of their design process (including expected information requirements between design activities) and using this information to plan the design process and allocate resources. One of the problems seem to be that they do not count with a clear method to identify if the information requirements they foresee between the groups of activities of their design process are matched in reality by actual information flows. Our assumption here is that with this additional information engineering design organisations can better understand if the performance problems they perceive on specific areas of their design process are mainly due to issues strictly related with the activities associated with that area and their participants, or are likely to be the result of an interface issue related to insufficient actual information flow (inputs) coming into the design space from other design spaces.

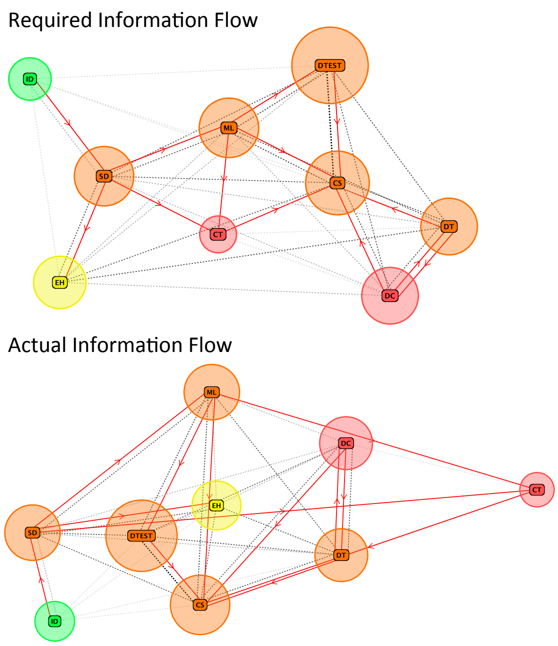


Figure 1: Visual comparison of required and actual information flows via force directed layout. Nodes are coloured based on reported performance.

From an academic standpoint, there are still unresolved issues with the modelling and comparison of required and actual information flows that current approaches are unable to address. Specifically, there are three main open challenges that motivate this research: First the possibility of accounting for multiple affiliations of people to design activities, second modelling actual information flows between activities instead of organisational units and third linking performance measures to the identified misalignments. In terms of accounting for multiple affiliations, methods able to quantitatively evaluate misalignments between actual and required information flows, such as a combination of Multi-Domain Matrix (MDM) and Delta Design Structure Matrix (ΔDSM), are limited to a 1 to 1 mapping of people or teams to activities or subsystems (Morelli et al. 1995; Sosa et al. 2007; Eppinger & Browning 2012). This simplification doesn't allow considering the multiple affiliations that a project participant can have over the course of a project, therefore limiting the scope of this approach. In terms of the second and third challenge, although there are recent examples in the network analysis literature of new approaches combining activities and people in the context of information flow analysis (Durugbo, Hutabarat, et al. 2011; Durugbo, Tiwari, et al. 2011), there is still no model to compare actual and required information flows and relate this comparison with their performance.

**The socio-technical network model and the collection method**

Since information flow levels and more in general all communication is contingent to each project and the requirements of each design activity, we found that to analyse the information flow a comparison point was needed, hence the notion of required and actual information flow was incorporated (see figure 1). To model the required information flows, a process based design structure matrix was selected as the key support to obtain structured information requirements in the design process. To model the actual information flow we collected through traditional social network analysis techniques work-related interactions between the members of the project, which were used as a proxy for actual information flows. Although with the network of activities and social interactions is possible to model separately the required and actual information flows, an intersection between them is still necessary to connect and compare these two flows. Therefore to analyse and compare systemically the actual and required information flows a formal connection between the process and the organisation was introduced via the addition of an activity-person relation based on the participation of a project member in one or more activities. In the study all the relations are weighted based on attributes such as frequency, dependency intensity and responsibility on the activity.

In our model, actual information flow between two design spaces can occur in two forms. One, project members affiliated with different design spaces interact with each other exchanging project related information. Two, the same project member can be affiliated to two or more design spaces, taking information directly from one space to the other (member co-occurrence). The amount of information flow between design spaces is calculated as a weighted combination of all paths between each pair of design spaces. To compute the information flow and to fulfil the requirements of our model we have used Stephenson´s and Zelen's (1989) "information centrality measure" between every pair of design spaces. This metric was selected instead of other simpler network measures such as geodesic distances, point connectivity or reachability because in our case it is critical to measure not only the shortest path in a dichotomous way but rather we required to quantify all paths connecting two design spaces taking also in consideration individual weights of each of the edges in those paths.

**The method to structure and quantify the required and actual information flow networks.**

Having defined the model and its constituent elements, we present a structured method to quantify and compare the required and the actual information flow networks. As figure 2 shows the method can be breakdown in three key steps: acquiring and quantifying the required information flow network, acquiring and quantifying the actual information flow network and comparing the required and actual information flows.

To acquire the actual information flow between design spaces two elements need to be gathered, the interaction network between members of the project and the affiliations of those members to design activities (or design spaces if that is the more detailed level available). The interactions between members of the project can be gathered via a structured interview to each of the members of the project, surveys, information system or a combination of these instruments. In order to weight the interactions additional questions about their frequency and impact are added. The affiliations to activities are obtained via the same means utilised to gather the interactions and weighted based on time invested on the activity and level of responsibility.

The amount of information flow between all pairs of design spaces is calculated as a weighted an undirected combination of all possible paths between design spaces, following the model previously introduced for this purpose. In order to compute the total information flow into each design space as well as the information flow between each pair of design spaces Stephenson & Zelen (1989) "information centrality" measure is used. This metric, unlike other network measures like geodesic distances, point connectivity or reachability, makes use of all paths between pairs of points, not just the shortest one, and in addition allows to consider weighted edges. Since in our model of actual information flow design spaces are never directly connected and the relatively reduced size and high density of the network translates into what Milgram (1967) described as a "small-world" network (with short average distances between design spaces), these features become essential to quantify and distinguish relative differences between the information flows.

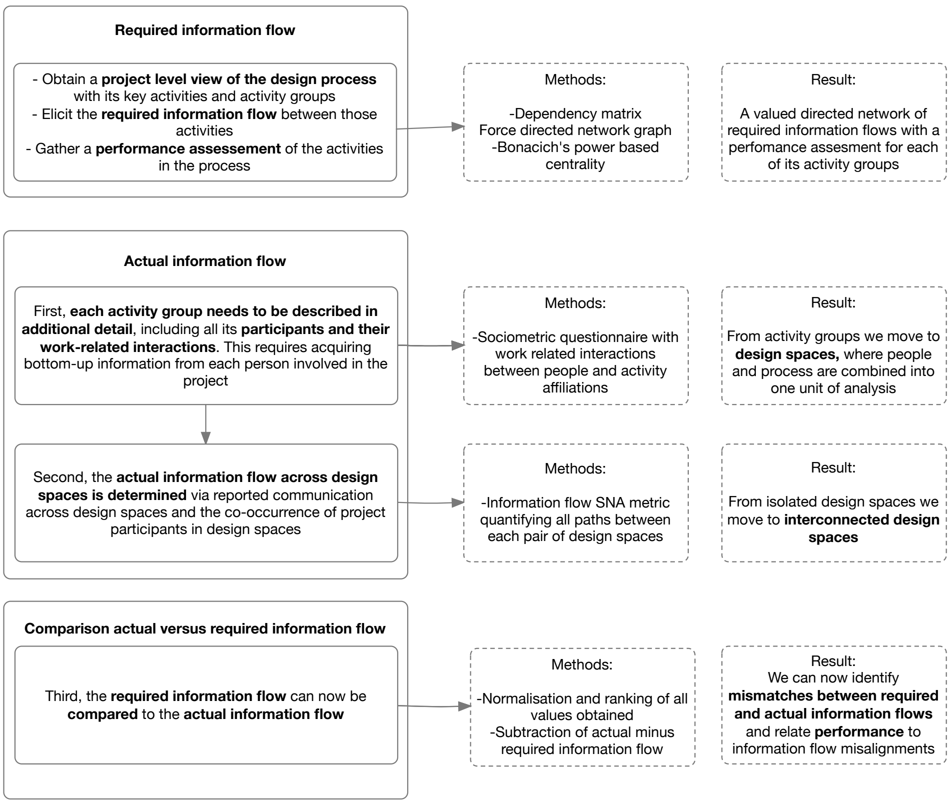


Figure 2: The three main steps of the proposed method.

## Conclusions

We devised this method because an important element to manage design engineer's work is to understand if the actual information flow they perceive while performing their activities matches what are believed to be the overall information requirements of the project activities they perform. What we found, is that it is not only possible to assess the degree of alignment between actual and required information flows, but that negative misalignments tend to be associated with lower than expected performance at the activity group level, corroborating the importance of being aware about these aspects.

Some advantages of this approach, compared to other network methods also employed at the intersection of process and organisational architecture, lie in its flexibility to affiliate people to any number of activities, regardless of their original department or team and in its simultaneous consideration of activities and people. This distinction allows for a more natural model of actual information flow, which acknowledges the fluid functional boundaries found in matrix organisations and other firms that frequently engage in complex engineering design projects. We expect this method to prove itself useful for the diagnosis and prioritisation of efforts at the communicational interfaces between sub-systems, allowing to more easily discern when performance issues might be due to insufficient information flows or are more likely to be the result of other issues in the design process.

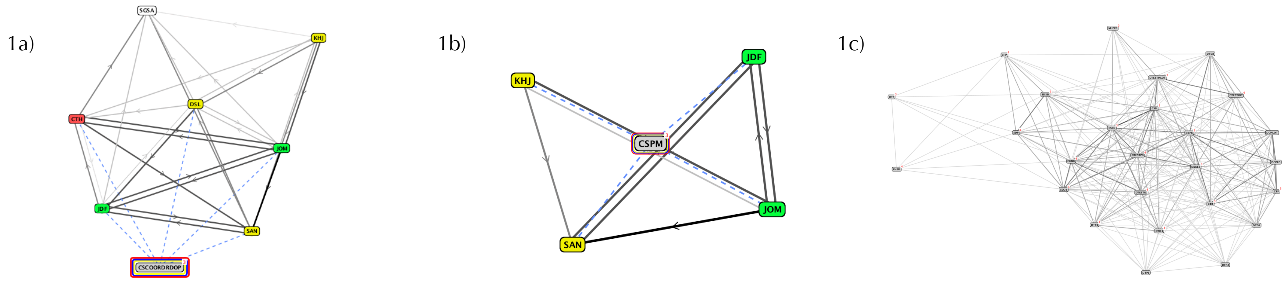


Figure 3: based on empirical data 1a) and 1b) show information networks around each design activity (coloured nodes represent people by their departments, grey nodes represent activities). Figure 1c) shows activities connected by social interactions.

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