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EVOLUTION OF INFORMATION CONTROL AND CENTRALISATION THROUGH STAGES OF COMPLEX ENGINEERING DESIGN PROJECTS

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1. Introduction

Complex engineering design projects are comprised of networks of interdependent activities, which in turn are implemented by networks of interdependent people. These people are assigned, both formally and informally, to project activities and then interact to execute activities and to exchange project related information. This project architecture defines how and why information flows between activities [Braha and Bar-Yam 2007]. Moreover, as the design process unfolds throughout its stages, we expect the way in which information flows between activities to evolve. This evolution through different stages can be traced to temporal and co-dependent aspects such as the progression of the design object, the maturity of the design process and the changing interaction patterns between and within people and activities. Considering this temporal evolution, we explore how the relative control that different activities have over information flow changes over time. This control can affect when and which activities are in position to intermediate or influence information in the project, which can in turn shape the temporal dynamics of the design process.

We define the *information control* (or influence) of an activity by its degree of intermediation on information exchanges. An activity's information control can be determined by its centrality within the information network and we can quantify this using a metric known as betweenness centrality. In addition, we define *information centralisation* as the overall distribution of information control, representing the centralisation of information flows in the project. Information centralisation can be quantified using a metric known as the group betweenness centralisation [Wasserman and Faust 1994]. To date, studies of the design process have not explored the temporal evolution of these measures and the significance of their evolution in the context of complex engineering design projects. Against this background this paper poses two main research questions: 1) *In what way do information control and centralisation change over the development stages of complex engineering projects?* 2) *What are the implications of these changes for engineering design theory and practice?*

The remainder of the paper is structured as follows: Section 2 provides theoretical background. Section 3 introduces the research approach used in our empirical study. Section 4 presents the results of our case study and answers question #1 above. Section 5 discusses the results and answers question #2. Finally, section 6 summarises the results and their implications for theory and practice.

## 2. Theoretical background: Views on the design process

The theory that informs this paper stems mainly from stage-based models of the engineering design process and from network analysis literature applied to engineering design and other socio-technical

systems. Our aim is to connect these two streams of studies of the design process by analysing the network structure of information flows throughout the stages of complex engineering design projects. In particular, we focus on network centralisation measures and on discerning which activities, at each point of time, are in position to exert greater influence due to their centrality in the information flow network. This approach allows us to show the evolution of control in information flows throughout a design project and reveals the existence of patterns connecting information control measures with key stages of the engineering design process. In this section we start by making explicit our systems approach through an information network model (2.1). We follow by stating our propositions about the expected implications of the design process stages in terms of information control and centralisation (2.2). We finalise by providing details about the network analysis concepts utilised (2.3).

2.1 A systems approach to the design process

Following Eppinger and Browning's approach to complex engineering systems [2012], we characterise the engineering design process as a system with three interconnected domains; the process, the organisation and the product domain. Each of these domains has its own architecture describing the relationship between its elements. In the process domain we find engineering design activities (also called tasks) connected by their information dependencies or other kinds of relationships. In the organisation domain we find interactions or other types of relations between people participating in the engineering design process. Finally, in the product domain we find the product components (grouped in subsystems if they exist) connected by different types of interfaces (spatial, energy, information, etc.). The architectures of these domains are usually represented and analysed using a design structure matrix (DSM) or by means of other network modelling techniques such as network graphs.

As the three domains relate to the same engineering design project, their architectures are interdependent. In fact, although the degree of mirroring between these domains varies across projects and organisations, previous studies have provided empirical evidence of this interdependence and have discussed the implications of misalignments. Examples of these studies include Morelli et al. [1995] describing the interdependence between organisation and process architecture and Sosa et al. [2004] applying a similar approach for the product and organisation architecture. Here we make use of this interconnectedness between domains to build an integrated and dynamical model of the engineering design process. Our specific emphasis is on the *process architecture as implemented through the organisation architecture*. This approach allows us to describe and analyse the actual temporal dynamics of the design process in contrast to the traditional form of modelling the process architecture based on reported dependencies (which describes instead the desired or believed structure).
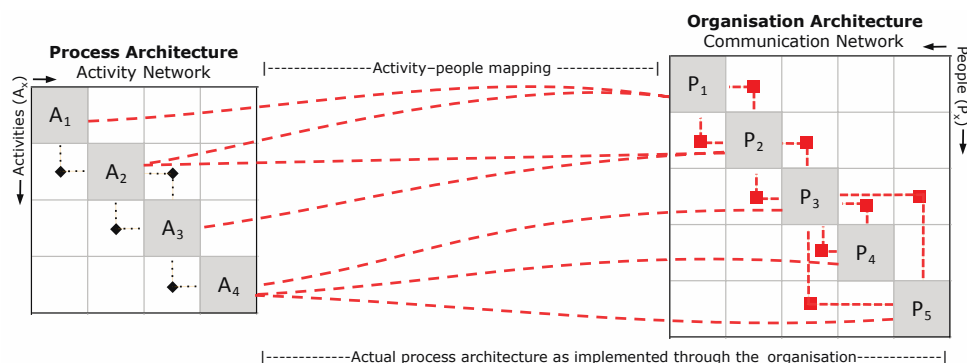
Figure 1. Construction of the process architecture as implemented through the organisation

In order to obtain the process architecture as implemented through the organisation architecture, our research approach models the engineering design process as a social process of information transformation (following Hubka et al. [1988]). In this process information flows between activities are connected and progressively transformed via people participating in the process. The model is operationalised as a multi-modal dynamic information network, which in its simplest form includes people interconnected via information-driven interactions and people doing information-related work in activities.

Figure 1 shows in schematic form how the *actual* process architecture is derived from the combination of interactions between members of the project, the process architecture, and the participation of people on activities. This composite network is highlighted as a red-dashed line and is a combination of the communication network and the activity-people mapping. As the applied analysis is dynamic, in reality these connections (edges) change over time, creating a set of snapshots that show the evolution of the design process from the point of view of its information network.

Although to obtain the actual process architecture we could have taken a more traditional process DSM approach, asking directly how activities are implemented using expert knowledge as done in [Browning 2002], [Eppinger and Browning 2012], the inter-temporal nature of our analysis would have made this task overly difficult for the respondents. The problem originates from the multiple ways in which activities can be implemented and connected to other activities. In other words, for any connection between a pair of activities, many people could be working on each activity, and any number of them may interact to implement the connection between their activities. Instead of directly gathering this dynamic network of task interactions from experts, our approach gathers first the mapping of people to tasks over time, then the interactions between people, and finally composes a unified network structure utilising this bottom-up perspective.

Part of the complexity of large engineering design projects is a result of the multiple intertwined processes being executed in parallel. To facilitate interpretation of the results, the process architecture subsequently shown here combines low-level activities into larger activity packages based on the common work they perform towards developing a particular subsystem or performing a sub-process. These activity groups can be seen as cohesive work packages of the design process and in order to simplify the terminology, from now onwards we will refer to them simply as *activities*.

In terms of the functions that activities perform, we have identified three broad categories: The first type are those activities doing engineering design work related to specific modules or subsystems under development; we call them *modular subsystem activities*. The second type corresponds to activities specifically designed to integrate two or more modular subsystems; we call them *integrative subsystem activities*. The third type of activities is devoted to the support and coordination of design work; we call them *integrative work activities* and they include aspects such as overall project management and procurement. The terminology used here follows Sosa et al. [2003] in identifying modular and integrative subsystems. The difference is that we have added the third category, integrative work, to recognise areas such as project management, which are expected to play a significant role in information control and coordination.

Using this approach the design process can be described at multiple levels of analysis. In this paper we will centre the analysis at the level of activity categories and the whole network of activities. However, with the same model and data it is also possible to analyse activities at a higher level of detail or elements of the organisational domain, including people, teams and departments.

2.2 Design process stages and their impact on information control and centralisation

Systematic models of the engineering design process, implicitly or explicitly, consider a logical sequence of stages and a set of activities within each stage. They model in this way a coherent evolution of the process with the objective of explaining or improving design practice [Wynn and Clarkson 2005, p. 35]. To guide this paper's discussion we will focus on the overall stages defined in Ulrich and Eppinger [2012] whilst applying the system development perspective found in INCOSE's systems engineering SE-V model [Haskins et al. 2011]. Despite this choice, the overarching points made here are applicable across different types of staged models. Based on these two models and the scope of our research, Figure 2 offers an overview of the stages that will be used as a reference point for this study. Our emphasis lies between the stages of conceptual design and system integration, as these are the limits of what is usually considered the predominant focus of engineering design [Clarkson and Eckert 2005, p. 5]. Consequently strategic planning and implementation are not explicitly covered.

Following the stages overlaid in the SE-V model of Figure 2 and their descriptions found in Ulrich and Eppinger [2012], we define a set of propositions about expected patterns of information control and

centralisation during each stage. These propositions will be later examined using the approach presented in section 2.1 and data obtained in our empirical case study.
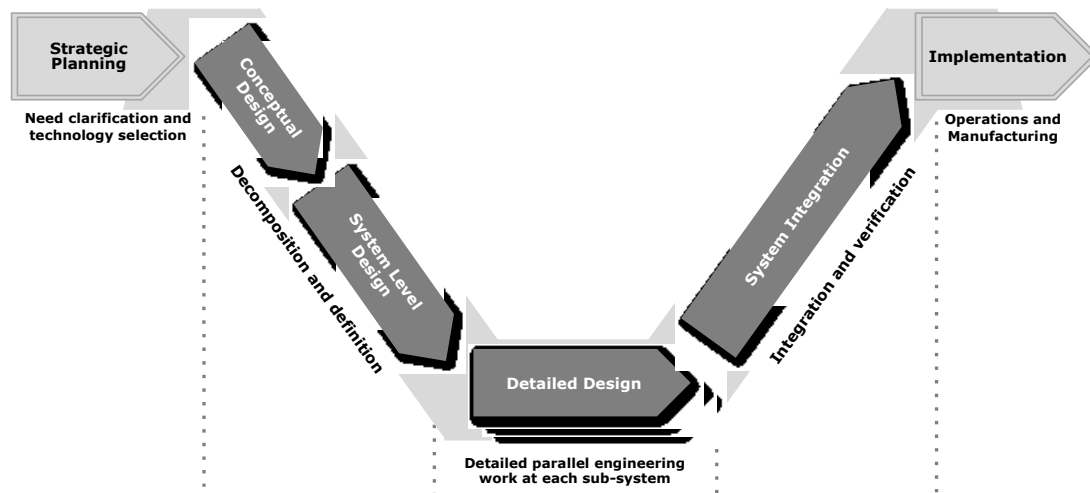
Figure 2. Stages of the engineering design process used in the context of this study. Adapted from Ulrich and Eppinger [2012] and INCOSE's SE-V model [Haskins et al. 2011]

During **conceptual design**, individuals from multiple functions contribute by providing inputs in the context of tasks such as idea generation, the selection of concepts and the preliminary planning of technical specifications. As most design considerations here affect the whole system and are usually very preliminary, we expect that only a few activities, mostly integrative work, will hold most of the information control, coordinating and aggregating information received from other areas.

During **system level design,** the overall architecture, agreed to in the conceptual design stage, is defined with additional detail, including the decomposition of subsystems into components. Preliminary engineering starts with a division of the work into multidisciplinary teams, assigned first to a core of relatively integrated subsystems, which usually require high levels of integration [Ulrich 2011, p. 88]. Because of these characteristics, during this stage we expect the previously high levels of information control held by the integrative work activities to decrease slightly. This is consistent with the work of the multidisciplinary teams interacting more directly to define the technical details at the system level. As the process of decomposition progresses and the subsystem teams gain more independence, a more fluid information structure with modular subsystem activities gaining information control is expected at the start of the detailed design stage.

During **detailed design,** the complete set of specifications is defined for all the components and the work is high in detail and granularity. As the degree of technical specialisation needed here reaches its peak, the subsystem activities perform more independently and in a relatively modular fashion. The assumption is that system level information acquired in previous stages provides enough information to enable relatively autonomous subsystem level work. In this stage we expect information control to be highly distributed, with no activity centralising the information of the whole project.

During **system integration,** components need to be tested and validated at the system level (which is the reason why this stage is sometimes named "testing and refinement"). Also all the modular subsystem activities have to integrate their results. Consequently, integrative subsystem activities are expected to gain information control and integrative work activities should have a higher information control than during detailed design. The information centralisation trend is also expected to rise as higher levels of integration are reached.

Table 1 summarises and compares the different features of the four stages in terms of our propositions about their characteristic information control and centralisation. In the table we also draw the shapes we expect for simplified information networks between activities. As information flow is not a binary concept, but rather a continuum of different intensities, we distinguish in the graph between strong and weak information flows.

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Table 1. Summary and comparison of expected features for engineering design project stages

Feature	Conceptual Design	System Level Design	Detailed Design	System Integration
Typical Activities	Idea generation, concept selection, and preliminary specifications.	Preliminary engineering, embodiment design, definition of subsystems and interfaces.	Technical development at each subsystem, complete specification of the components.	Testing and validation at the system level, if necessary rework.
Areas expected to control information	Project management (integrative work).	Project management progressively decreases its control while modular subsystem activities increase their control.	Integrative and modular subsystem activities.	Integrative work and integrative subsystems increase their control.
Expected information centralisation profile	High but decreasing. Only a few areas control information.	High to medium but decreasing. Information control becomes more distributed.	Low and slowly increasing. Information control becomes highly distributed.	Medium and increasing as a few integrative areas gain information control.
Expected structure of the information network				

Legend:
○ Modular Sub-system Activities ◇ Integrative Work Activities □ Integrative Sub-system Activities —— Strong Information Flow ······· Weak Information Flow

2.3 Network analysis of engineering design projects

Network analysis as a conceptual approach and an analysis technique has been applied to model and understand complex engineering systems and related areas for over 50 years. Key learning points from work in this area relate to a better understanding of complexity and how this complexity emerges from the interactions or relations of elements in a system. Elements, on their own, may be rather simple. Yet, when combined, their interactions may lead to the emergence of rich and sophisticated system behaviours. Network analysis focuses on these interactions and aims to provide quantitative means for their study and interpretation.

In this paper, and as described in section 2.1, we model the engineering design process as an information network. An information network is taken to be a system representation of the information transformation process, where the elements (nodes) are connected by information exchanges (edges). Elements may be people, activities, documents, or software platforms. Such elements can be combined into a multimodal network (where different kinds of elements co-exist) or as a one-mode network (where only one type of element is represented). Each node can be described using network measures that quantify their direct and/or indirect connections. Likewise, the network as a whole can also be described based on the structure of its connections (in our case information exchanges). The advantage of network measures over observations or simple graphs is that they provide quantitative means to characterise the patterns found on the system under analysis. Table 2 shows the network measures with applications to information networks that we use in this study. As a proxy for information control and centralisation, we use node betweenness centrality and group betweenness centralisation. These are the most commonly accepted measures of centralisation in a network and also of information control in the context of information networks [Freeman 1979], [Wasserman and Faust 1994, pp. 189–192], [Cross and Cummings 2004], [Collins et al. 2009]. For an overview of alternative centrality measures and a discussion of their features see also Bonacich [1987].

To date, most studies using network analysis metrics to describe and analyse the engineering design process use aggregated data illustrating snapshots of specific (static) points in time (e.g. Yassine et al. [2003], Batallas and Yassine [2006] and Collins et al. [2010]). We complement their work by contributing to the evolution of the network metrics and their connection to the stages of product development; in other words, by adding temporal dynamics of the information flow across the stages of an engineering design project. Therefore, instead of a static and aggregated analysis of the network, what we do is to analyse each of these measures at different points of time. To operationalize this and as suggested by Vespignani [2011] and Kossinets and Watts [2006], temporal network analysis can be

used to reveal both the evolution of the whole network and the co-evolution of subsystem or elements within the network. Recent examples of applied temporal network analysis include a visualisation of the evolution of knowledge structures in an organisational setting [Štorga et al. 2013] and an exploration of temporal patterns in the way designers gather information using students in a controlled lab setting [Cash et al. 2013].

In order to implement the dynamic network analysis centred on betweenness centrality and group betweenness centralisation, we have followed the temporal communication flow structure proposed by Gloor and Zhao [2004] and used the Condor software package [Gloor 2013]. By doing this we have expanded their original application areas and introduced new interpretations and network models specifically developed for the analysis of the engineering design activity.

Table 2. Details of selected network measures and their relevance in information networks

Network Concept	Description of Network Measure	Meaning in Information Networks
Node Betweenness Centrality (BC)	Proportion of shortest paths from all nodes to all others that pass through the node in question. If all paths have to go through the node the number is 1, if there is always an alternative path the number is 0.	Nodes with high betweenness centrality are more likely to act as intermediaries on information exchanges and can therefore exercise more control or influence on those exchanges.
Group Betweenness Centralisation (GBC)	Distribution of betweenness centrality across the nodes. The index reaches its maximum value (unity) for the star graph where the entire network has one central point. Its minimum value (0) occurs when all nodes have exactly the same betweenness centrality.	High group betweenness centralisation is a sign of a centralised information exchange architecture, were one or only a few groups intermediate most information exchanges. Low group betweenness centralisation is an indication of decentralised and horizontal information flows.
Graphical Summary		

GBC = 1
BC(A) = 0, BC(B) = 1

GBC = 0
BC(A) = 0

GBC = 0
BC(A) = 0.16

GBC = 0
BC(A) = 0

3. Research approach and methods

In order to perform the empirical part of this study a complex engineering design project was used as a case study. The project consisted of the complete engineering design work of a biomass power plant for energy generation developed in the period between 2010 and 2013. Information about the design process of this plant was obtained through the company's information systems, documents, interviews with the top management, and electronic questionnaires to the core developing team. Table 3 provides a summary of the key data gathered and additional details about its characteristics.

Table 3. Case study data

Data	Description	Relational information	Temporality	Main source
People	96 project participants divided into 15 departments	Reported work-related interactions between people and participation of people on activities	Inferred through the temporality of activities, documents, and reported interactions	Electronic questionnaire
Activities	203 activities in 13 activity groups, subsequently divided into 3 categories	One or more people perform each activity	Each time an activity is performed by someone, it is registered with a timestamp and a number of hours (11,742 activity entries)	Company records

Activity list and categories

Integrative work activities:	Integrative subsystem activities:	Modular subsystem activities:
- Overall project management - Procurement - On-site coordination	- Design of steel structures - Load plan and layout - Process flow diagram (PFD) + piping and instrumentation diagram (P&ID) - COMOS (plant engineering platform)	- Boiler and equipment design - External piping design - Pressure parts design - Air and flue gas design - Combustion system design - Electrical, control and instr. design

4. Analytical results from our case study

In this section, we present the results of applying temporal network analysis to the information network of our case study. Our results describe the evolving design process and are presented at two levels of analysis: activity categories (4.1) and the whole information network (4.2). Our focus is on the evolving process architecture (activities) as implemented through the organisation architecture (people). As a representation of these architectures figure 3 shows four graphs, one per process stage, built using the model presented in Figure 1 and the case study data. Black nodes represent the 13 activity groups and grey nodes the 15 departments (nesting people in their departments in order to simplify the visualisation). The edges between departments are work-related information exchanges. In turn, the edges between activity groups and departments represent the participation of those departments in activities from that group. The structure as a whole describes the sum of information flow paths at each stage of the project, and the overall network topology provides an indication about relative centralisation of the information at each of the studied stages.
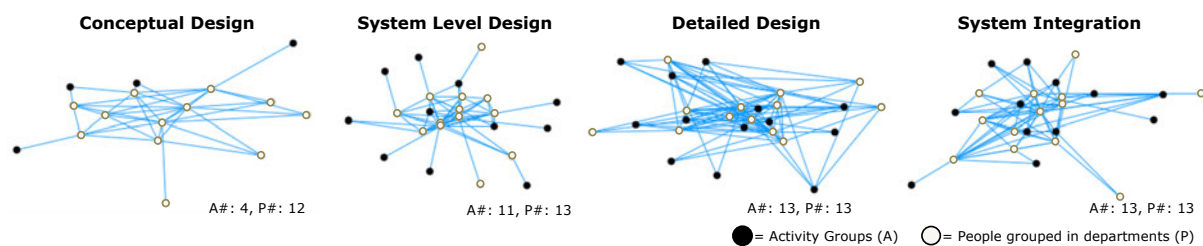
Figure 3. Information network for each of the analysed stages.
Activity groups and departments are connected following the approach introduced in figure 1

Through Figure 3, we can see the changing number of departments and activity groups alongside their evolving connectivity patterns at an aggregated level of analysis. In this aggregated network topology the evolution of information control and centralisation is hidden in the details of the dynamic structure. In what follows we show how applying quantitative dynamic network analysis, and in particular betweenness centrality and group betweenness centralisation, distinctive patterns emerge that allow us to characterise the information control and centralisation at each of the stages, helping to answer research question #1.

4.1 Information control across activity categories

Figure 4 depicts the evolution of betweenness centrality for each of the three categories of activities previously defined. (To do this, we compute betweenness centrality for each activity category as if it were a single activity). From this figure we can observe, leaving conceptual design aside, that the expected patterns for the evolution of information control between the three activity categories do in fact emerge. System level design starts with integrative work holding high information control, which declines over time as the modular subsystem activities enter during that stage. Detailed design is dominated by development of the modular and integrative subsystems, with a sharp decrease in control by integrative work activities. In turn, during the system integration stage, control by activities related to integrative work increases, integrative subsystems remain at the levels of detailed design and modular subsystems decrease their control over time.

In the conceptual design stage, we see information control alternating between integrative work and modular subsystem activities, whereas only the former had been expected. To understand this result, two elements specific to our case study appear to be relevant. First, the volume of activities recorded at this stage was low, so we had to use the betweenness centrality of the closest organisational department as a proxy of activity betweenness centrality. In practice, this should introduce only minor distortions, as the functional groups map closely to the process architecture. Second, the company had extensive prior experience in these kinds of projects. This allowed key technical areas (a few modular subsystem activities) to lead during the conceptual stage of the project. This result is illustrative of the differences between repeated projects, which can leverage previous experience, and new ones.

4.2 Evolution of information centralisation at the project level

Figure 5 shows the group betweenness centralisation (GBC) calculated for each month of the project after aggregating daily registers. GBC, unlike betweenness centrality, which is a node-level measure, describes the whole network centralisation and can be interpreted as a measure of the distribution of information control among different activities (and consequently subsystems) in the project. A high GBC indicates that most of the information control is held by only a few activities and therefore information flows tend to be more centralised. The lowest GBC (0) means that information control is evenly distributed and can be interpreted as a sign of high process modularity and relative autonomy between the subsystems under development. Despite oscillations in the measures (partially due to periods of inactivity), Figure 5 shows evidence of patterns that match the expected evolution of GBC at each of the stages of the project. Conceptual design is characterised by only a few activities holding most of the information control and coordinating inputs from multiple areas. System level design exhibits a similar pattern that decreases over time as detailed design is about to start. Detailed design shows signs of increased process modularity due the high technical specialisation and level of detail work (reflected in its low GBC score). Finally, system integration shows a rising GBC score, a sign of the needs for higher levels of coordination at the end of this stage to complete integration of the different subsystems.
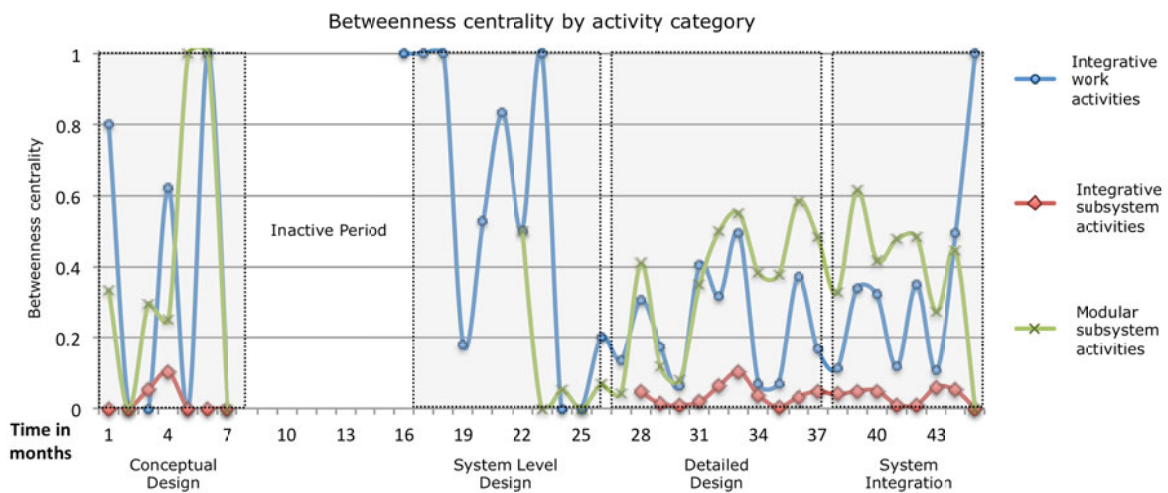

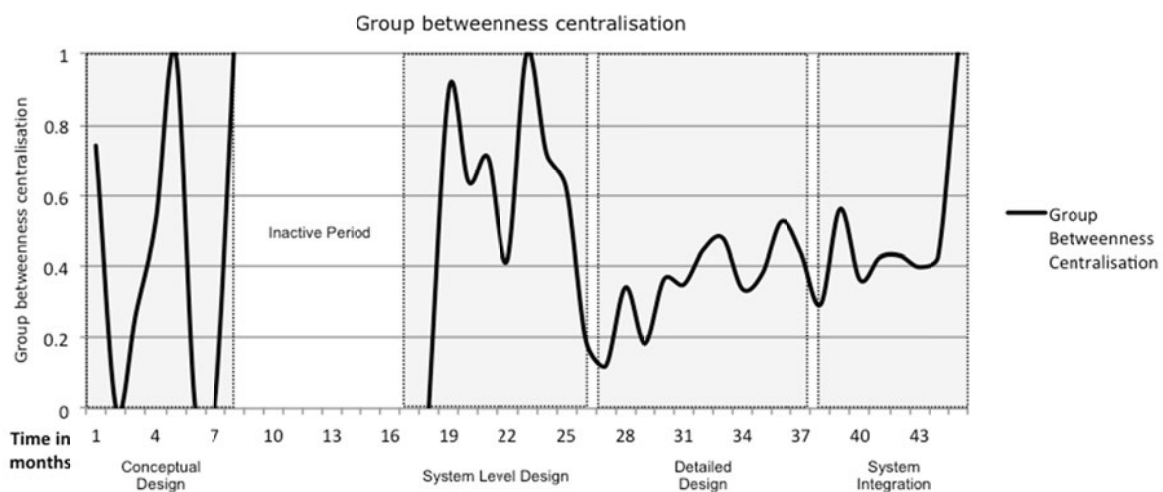**Figure 4. Evolution of information control across activity categories, measured through BC**

Figure 5. Evolution of information centralisation, measured through GBC

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5. Discussion

In our empirical results, we found evidence linking the evolving measures of betweenness centrality and group betweenness centralisation with the expected information control and centralisation features at several stages of the design process. This evidence is consistent at the two levels of analysis presented. At the level of activity categories, we see how the three categories exhibit a distinctive behaviour over time, matching our prediction for three out of four stages. These patterns not only validate our predictions, but also suggest a meaningful macro-level categorisation of activities, founded not just on observations and conceptual models but also on their characteristic network dynamics. At the whole network level, we see how the changing distribution of the information control follows a pattern that can be linked with process modularity and SE-V model stages.

Although our evidence only comes from one case study, this paper can be seen as a proof of concept that both the model and applied methodology are able to produce meaningful results. Furthermore, our findings have been validated through interviews and presentations at the company, providing evidence that our results are representative of real design process dynamics operating within this engineering design project. Through this qualitative feedback, we were also able to explain the patterns that differed from those expected for the generic stages, which in most cases had roots in the specific features of the project, evidencing the contingent nature of designing.

One interesting result of the application of this approach is that we not only see the evolution of the whole network but also the different trajectories that individual activities follow during the course of the project. This shows the intertwined nature of design processes, where multiple activities and different time-scales and rhythms operate in parallel at each developed subsystem (which is particularly relevant in the lower part of the SE-V model, where detailed design happens).

A key feature of our approach is the idea of contrasting real designing patterns, in our case the evolving structure of the information network, with models of the design process. Aligned with the arguments of Clarkson and Eckert [2005, p. 21] about studying the reality of design via "designing patterns", we believe that the deep exploration of such patterns provides valuable insights to complement the prescriptive approach of design process models, helping to unveil potential causal explanations for the observed design phenomena.

6. Conclusions

In this paper we have shown how through a temporal network analysis of the information flows between activities we can uncover a view of the design process that provides new insights to connect stage models with the dynamics of the process architecture. As a result of this approach, we foresee implications for theory development and practice. From the theoretical viewpoint, we have provided evidence of relationships among betweenness centrality, group betweenness centralisation, information control and design stages, which serves to quantify specific properties for different stages of the design process. This enriches previous descriptions and interpretations of the stages and may allow design researchers to develop process models that better fit observed project patterns.

Implications for engineering design practitioners, and especially project managers, include the possibility of providing a quantitative overview of real designing patterns, which can be compared against prescriptive models. Moreover, when applied at a more detailed activity level, our model highlights periods in the process where multiple areas concurrently increase their information control, potentially draining resources and generating complex coordination scenarios. Knowing more about these periods can help to defer activities that do not need to be concurrently active, while prioritising the ones with coupled subsystems that do require concurrency or iterations.

One limitation of our approach is related to the availability of rich temporal and relational datasets. In addition, when these datasets exist, their reliability does not always allow this type of analysis. In order to replicate and make scalable the use of this approach in industry, it is necessary to limit the time required to gather this information, tap into existing company systems and standardise the process.

Interesting venues for further research in this area include comparisons of betweenness centrality measures across different projects and industries. This would allow evaluating if the overall patterns are stable or are project or industry specific. In addition, more research is required to explore the

evolution of other network measures and their interplay with betweenness centrality. Observed process architectures as implemented through organisations could be compared to planned processes. Finally, further studies could use dynamic network measures as independent variables and performance as a dependent variable in order to establish concrete connections between network structure and results.

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