# UNFOLDING THE DESIGN PROCESS ARCHITECTURE: A NETWORKED PERSPECTIVE ON ACTIVITIES

**Parraguez, Pedro; Maier, Anja M.**
Technical University of Denmark, Denmark

## Abstract

A number of network-based process models have been developed to guide the design of engineering systems. Many such models represent design activities only as single nodes. As a result, the architecture, i.e. the network structure and composition of each activity, remains invisible and inaccessible for further analysis. However, when we unfold the architecture of activities we see the organisation network through which activities are conducted by people. The architectures of such organisation networks matter as they affect performance outcomes of activities.
We propose and empirically test a framework for systematic characterisation and subsequent clustering of activities based on the architecture of the activities' organisation networks. Architecture characteristics examined include network size, network density and compositional diversity. The proposed framework not only enriches current process models, but also enables a more systematic analysis of the relationship between the organisation network of each activity and performance. The framework is tested with data from the design process of a biomass power plant where we identified architecture-performance relationships.

**Keywords**: Complexity, Design process, Organisation of product development, Network analysis, Design activity

**Contact**:
Pedro Parraguez
Technical University of Denmark
Management Engineering
Denmark
ppru@dtu.dk

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## 1 INTRODUCTION

The overall process architecture when designing engineering systems is often characterised by using activity network models (e.g. Browning & Ramasesh, 2009). Characterising the process architecture reveals a map of input-output relationships between activities, which is important as relationships are what give processes their added value (Eppinger & Browning, 2012, p.133; Rechtin, 1990, p.29). Process architecture models also allow untangling complexity, making processes more manageable and transparent. However, in activity network models such as the one represented in figure 1, each activity is described as a single network node and treated as a black box that takes information inputs and delivers information outputs. As a result, the architecture of each activity, i.e. the structure and composition of the organisation network that performs each activity, remains invisible and inaccessible for further analysis and actionable insights. At the same time, it is widely acknowledged that the way a system is architected influences its behaviour. Phrased differently, a well-crafted architecture should contribute to more desirable outcomes.
With this background: How can we model and quantitatively characterise the architecture of each activity? How can we use such characterisations to reveal insights that support the management of design processes?

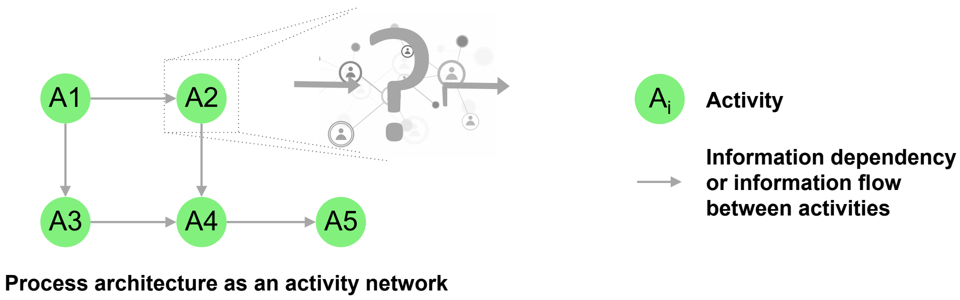


*Figure 1. The invisible network architecture of each design activity*

The objective of this paper is to provide a framework that unfolds the architecture of activities, making the network that performs each activity visible and quantifiable. Unfolding the architecture of activities in a design process also provides means to assess the relationship between the structural and compositional network characteristics of activities and their performance. This, in turn, allows for enhanced process reflection and tailored support strategies (Maier, Kreimeyer, Hepperle, *et al.*, 2008).
This paper is part of a larger research project that studies the patterns of communication through engineering networks implementing a development process. The overall research project has been broken down into three levels: Individual activities (the work presented here), process interfaces, and the dynamic evolution of the whole process (Parraguez, Eppinger & Maier, 2014). A key objective of the project is to explore the relationship between network architecture and performance outcomes through what we have termed the Networked Process Framework (the NPr Framework).
The remainder of this paper is organised as follows: Section two provides a literature background, synthesising three literature streams on studying and supporting the design process at different levels and units of analysis. Section three proposes a network-based framework for unfolding and quantifying activities' architectures. As a proof-of-concept, section four applies the framework to the engineering design process of a biomass power plant and evaluates the relationship between activities' architectures and activities' performance outcomes. Section five concludes with implications for design research and practice.

## 2 LITERATURE BACKGROUND

We argue that there are a number of complementary literature streams that contribute to and benefit from a networked perspective to systematically unfold activities' architectures. These academic streams can be broadly divided into: studies that focus on defining and describing design activities in detail, yet do not make a direct connection with the overall process architecture (2.1), studies that characterise design activities as a single node in the context of an overall process, yet do not describe the architecture of the activity itself (2.2), and studies that provide means to connect the whole process architecture with the architecture and the work outputs of each activity (2.3).

## 2.1 Studies on design activities

A design activity may be defined as the actions taken by one or more people in order to achieve a design goal. Such actions may be executed individually or in a team to transform a set of information inputs into a set of information outputs. The goal of a design activity may relate to the definition or evaluation of a parameter of the design object to be developed, or the management of the design process (Sim & Duffy, 2003). In engineering design, empirical studies at the activity level have contributed with rich descriptions about the work that is performed at each activity, the micro details of interactions, observing and capturing the behaviour of the people involved in an activity, the way one activity may feed into the next, what people's rationale may have been, what the specific situation may look like, what outputs were created and so forth. See, for example, studies using *linkography* (Goldschmidt, 2014) and ethnographic observations of design activities (Bucciarelli, 1988). Such characterisations permit detailed insights, yet, do not explicitly connect with the overall process architecture. Further, they tend to be resource-intensive and thus make detailed activity characterisations hard to implement, scale and maintain updated in the context of large engineering design projects with dozens or hundreds of activities.

## 2.2 Studies on the architecture of the whole design process

At the level of the whole design process, activity network models are widely accepted means to increase process overview, to quantify, and to optimise the architecture of processes (Browning and Ramasesh, 2009). Examples of such models include Design Structure Matrices (Eppinger and Browning, 2012), Signposting (Wynn *et al*., 2006), IDEF0, IDEF3, PERT, Petri-nets, or workflow diagrams. Studies have also provided empirical evidence for relationships between the architecture of the overall design process and process performance (e.g. Collins *et al.*, 2009; Browning & Eppinger, 2002), highlighting the importance of quantifying architectures.

In addition to including information on activities and their relations, some process architecture models also connect with the architecture of the organisation that performs the engineering design project – thus permitting incorporation of more details about each design activity. Further, connections between the process architecture (links between activities) and the organisation architecture (links between people such as communications) have been operationalised through the use of single-domain matrix-based approaches, where each activity can be associated with one organisational unit or person (one-to-one relationship), e.g. 2D DSMs (Morelli, Eppinger & Gulati, 1995; Sosa, Eppinger & Rowles, 2004), multi-domain matrix-based approaches (Yassine, Whitney, Daleiden, *et al.*, 2003; Lindemann, Maurer & Braun, 2009), or bi-modal network-based approaches (Durugbo, Hutabarat, Tiwari, *et al.*, 2011). However, despite the increased flexibility of such approaches, they have so far not explicitly modelled the architecture of each activity and connected it to performance measures at the activity-level.

## 2.3 Studies on organisation architecture and engineering design information traces

To characterise organisation networks (interconnected people) we can draw on previous studies, which in the context of the design process (e.g. Batallas & Yassine, 2006; Cross & Cross, 1995), and analyses of teamwork (e.g. Crawford & LePine, 2013), provide evidence about the benefits of characterising how design is organised and provide means to perform such characterisation.

A different line of research refers to the identification of patterns in the design process through an examination of the digital objects and information traces produced during the design process (e.g. Snider *et al.*, 2014; Pavković *et al.*, 2013). These approaches can be used as a lever for the systematic and scalable characterisation of the architecture of each activity, structuring pre-existent digital traces about the architectures of process and organisation.

While such studies provide insights into how people interact in the context of design activities and show the multitude of outputs produced, a disconnect remains between the patterns those studies identify and the overall process architecture. This distance from the process architecture is further increased as the focus is not on individual design activities but on people and their design outputs.

## 2.4 Gap in literature

What is missing in design process literature is the middle ground between a detailed characterisation of each activity, which is often not scalable given its resource intensive nature, and those models that characterise the whole process architecture but do not provide a network characterisation for each activity. This disconnect between the process architecture and the architecture of each of its activities limits our understanding of how the organisation of each activity affects activities' performance outcomes. It also makes it more difficult to identify best practices and potential problems at the level of each activity.

Therefore, we propose a framework that unfolds the architecture of each activity by describing and quantifying the organisation network that performs each activity. The framework includes a conceptual model and a method that allows a systematic and scalable characterisation of the network architecture of activities. This framework is positioned to fill the gap between approaches that characterise activities in detail (2.1) and high-level whole process architecture approaches based on activity networks (2.2). It does this by drawing on research in organisation architecture and on engineering design information traces (2.3). The proposed framework intersects process and organisation architectures and also leverages automatically captured data that most organisations are already gathering as part of their normal operations.

# 3 A FRAMEWORK FOR THE STUDY OF NETWORKED DESIGN ACTIVITIES

To respond to the identified gaps and the need for a systematic and scalable characterisation of activities' architectures, the framework proposed here consists of a conceptual model (3.1) and a method to quantitatively operationalise the model and to test the relationship between the architecture of activities and performance measures (3.2). The framework is predominantly descriptive in nature and seeks to capture the actual architecture of design activities by organising data traces produced throughout the process.

## 3.1 Model: Design activities as organisation networks

In order to unfold the architecture of each activity and bridge detailed activity characterisations (2.1) with overall process architecture approaches (2.2), the model proposed here utilises the overall organisation architecture and the mapping of people to activities to build the network architecture of each activity.

Following network analysis literature, the network architecture can be characterised in terms of the relationships between the elements (structure) and the type of elements involved (composition) (Wasserman & Faust, 1994). Also, albeit coming from different theoretical standpoints, when characterising activities, works on activity theory (e.g. Engeström *et al*., 1992) and studies on organisations as networks (e.g. Durugbo *et al*., 2011) include the following primary aspects to characterise an activity:

**Structure:**

- The amount of people participating in each activity, as this is said to impact aspects such as coordination and availability of knowledge (size of the organisation network);
- The connectedness of the people involved in each activity, as the density of the organisation network can affect the efficiency of information flows. This includes the degree of intensity and actual distribution of the workload and responsibilities of each of the participants in an activity, as this can reveal patterns about how activities are organised

**Composition:**

- The compositional diversity of people, as heterogeneous groups can draw from a more diverse pool of knowledge but are also faced with more communicational challenges.

Against this background, Figure 2 shows a fictitious example including the information inputs required to execute the model:

- The process architecture (top left quadrant of the Multi Domain Matrix (MDM)) as a weighted and directed activity network, which can be obtained through interview or process mining.
- The organisation architecture (bottom right quadrant of the MDM) as a weighted organisation network plus selected attributes about the people participating in the process. All of which can be captured from questionnaires, email metadata and/or other communication tools.
- A weighted mapping of activities to people (the other two quadrants of the MDM) in the form of a Domain-Mapping Matrix (DMM) based on affiliation of people to activities and the strength of their affiliation. All of which can be captured from questionnaires and/or process mining of activity logs.

With such information inputs is possible **to build a model for the network architecture of each activity** that captures aspects about the structure and composition of each activity that are often unaccounted for.

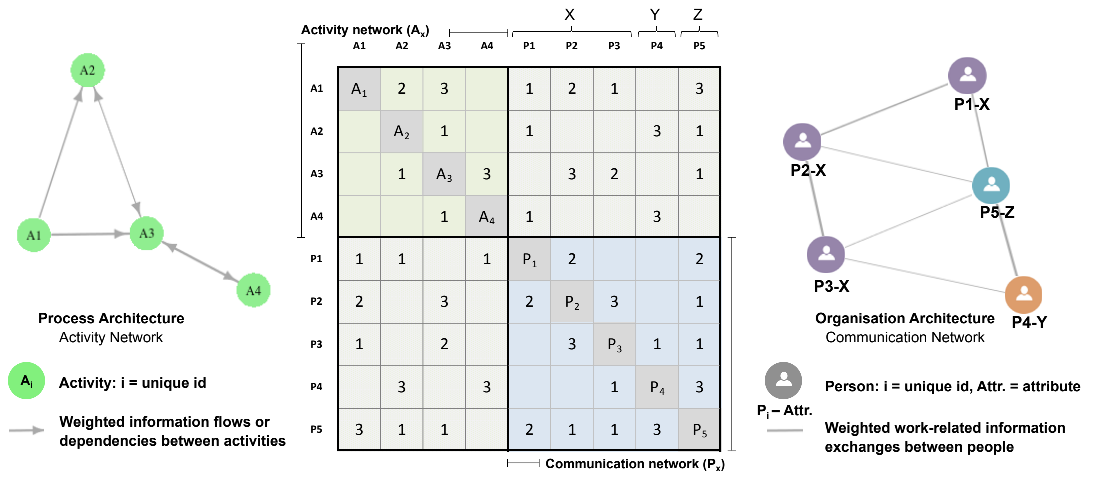


*Figure 2. A fictitious example illustrating the weighted information inputs to build the model. All matrices follow the inputs in columns convention (IC).*

Figure 3 shows the results of applying the model to the example presented in figure 2. More specifically, figure 3 illustrates for Activity 1 (A1) and Activity 2 (A2) how each activity can be **unfolded to reveal its inner architecture**, including all the primary aspects previously described. For instance, if we take attributes X, Y and Z as departments and the weighted affiliation as a combination of responsibility and amount of hours invested, Activity 1 (A1) can be characterised as a network of four people (P), with three people from department X and one person from department Z. On a scale from one to three, P1 and P3 are only affiliated to the activity with strength of one, P2 with a strength of two and P3 with strength of three. Only P1 and P3 have not had a direct work-related information exchanges while all the other members exchange information directly and with a variety of intensities.

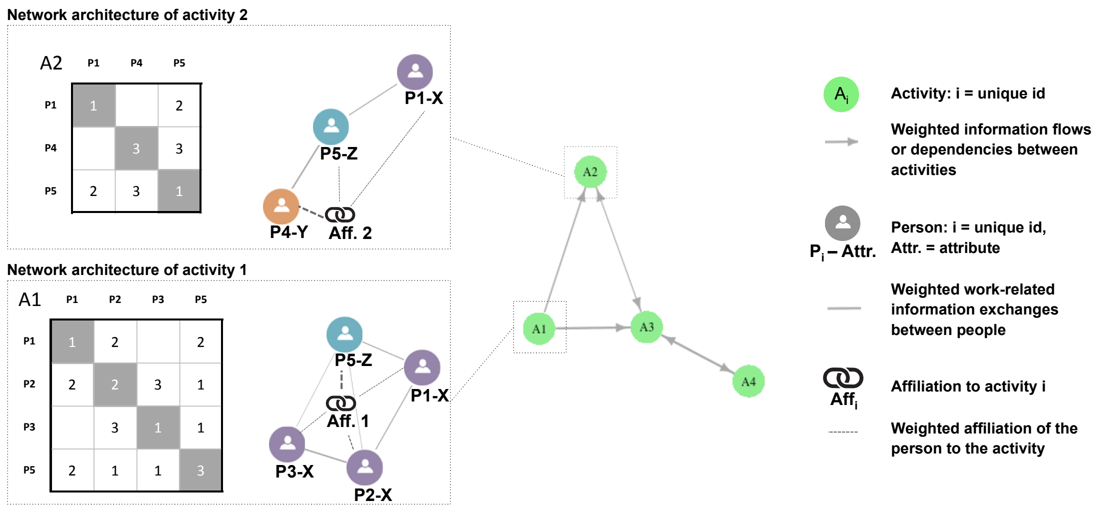


*Figure 3: Results of applying the model to unfold activities A1 and A2 from the fictitious example presented in figure 2. On the left, a modified weighted organisation DSM and a network graph showing the network architectures of activities A1 and A2. The diagonal of the matrices show a measure for the strength of affiliation of each individual to the activity.*

## 3.2 Method: Quantitative characterisation and analysis of activities' architectures

To advance from the model previously discussed to a systematic characterisation and analysis of activities architectures, we need a method that quantifies the architecture of activities in terms of their structure and composition (3.2.1). Once each architecture is quantified, we need another method that allows using the characterisation to analyse patterns across activities architectures, enabling the assessment of the relationship of those patters with performance measures at the activity level (3.2.2).

#### *3.2.1 Activity characterisation*

- To quantify **structure**, this paper uses the following measures: **network size** as the number of people taking part in the activity, and **weighted network density** as the sum of all edges in the network architecture of the activity divided by the theoretical maximum of the sum when such network is fully connected (Wasserman & Faust, 1994, p.101)). In order to capture the degree of affiliation to the activity we include the edge that accounts for the strength of the affiliation as part of the network when calculating density (diagonal of the matrices in figure 3).
- To quantify **composition**, this paper uses the **Index of Qualitative Variation (IQV)** (Agresti & Agresti, 1977). The index provides a measure of network heterogeneity that goes from zero to one. Zero means no heterogeneity (all people involved in the activity have the same attribute) and one means maximum heterogeneity (each person participating has a different attribute).

Following the example provided in figures 2 and 3, we can now quantitatively characterise the architectures of A1 and A2 based on the above measures. **Size:** A1=4; A2=3 **Density:** A1=0,52; A2=0,56 **IQV:** A1=0,56 A2=1. While size, density and IQV are able to capture primary aspects of the architecture of activities and are simple to interpret, a number of other network and non-network metrics can also be used to quantitatively characterise the model proposed in Section 3.1. See (Kreimeyer & Lindemann, 2011) for a review of complexity metrics in Engineering Design.

#### *3.2.2 Analysis of activity architectures*

Once all activities are characterised in terms of size, density and IQV, we can start to examine if patterns in the characterisation of the activity architecture emerge. Subsequently we can also test if there is a relationship between a detected pattern and associated performance measures at the activity level. An approach to achieve this is to start by clustering activities in groups, using the previously quantified characteristics as clustering variables (size, density, and IQV for compositional diversity). If quantitative performance measures of efficiency and/or effectiveness are available for the activities, each of these performance measures can be calculated per cluster and used to test for statistically significant differences on performance levels between clusters. If differences indeed exist, they can be used as evidence that certain types of activities architectures are related with different levels of performance outcomes.

One method to find clusters in a set of activities is the two-step cluster analysis. Using this method, each activity is assigned to one cluster based on the compositional and structural characteristics of each activity organisation network. A one-way ANOVA test can be used afterwards to test for significant performance differences between the resulting clusters. If the clusters in the one-way ANOVA test show a statistically significant difference in performance, then a more detailed analysis can follow to clarify potential causality between architecture and performance. This, in turn, provides the basis for targeted interventions to the activities' architectures. Even if statistically significant differences are absent, the clusters can still be used as a way to generate groups of activities that share similar features and are therefore likely to require different management strategies.

## 4 FRAMEWORK APPLICATION

To demonstrate the practical application of the proposed framework we use data from the engineering design process of a biomass power plant (4.1). As a result, we show how the framework provides a systematic and scalable characterisation of activities' architectures as well as insights about the relationship between architecture and performance outcomes (4.2).

### 4.1 Acquiring case study data on the design process of a biomass power plant

A large engineering design project was used as a case study to test the proposed framework. The project consisted of the complete engineering design work of a biomass power plant for energy generation. The plant was developed in the period between 2010 and 2013.

Information about the design process of this plant was obtained through the company's own information systems, documents, interviews with top management, and electronic questionnaires to the core development team. For the purposes of this paper, the following sources were used: historical

data from activity logs, questionnaire data on work-related information exchanges between core project members, and data logs on activity performance, including schedule overruns and revisions to existing documents from the company's document management and hourly budgeting systems.
On the activity level, two performance measures were obtained from the company's management system: Scheduled hours overrun (difference between actual and planned hours) and the average number of document revisions per activity. The amount of hours overrun per activity was used as a proxy for efficiency. The average amount of document revisions was used as proxy for effectiveness. Following the model presented in 3.1, data was gathered to define the process architecture (4.1.1), organisation architecture (4.1.2), and to perform a mapping between process and organisation architectures (4.1.3).

#### 4.1.1 Process architecture data

To manage the engineering design process of the power plant and its many sub-systems, the company assigned a unique code to each design activity. From a total of 148 unique activity codes, and for the purposes of this study, 44 activities were selected based on the following criteria: Two or more people needed to be involved in each activity and performance indicators of the outcome of the activity needed to be available.

#### 4.1.2 Organisation architecture data

We distributed an electronic questionnaire to obtain the communication network as weighted work-related information exchanges between core project members of the design process. All 49 core project participants from 15 engineering departments completed the questionnaire, yielding 756 dyads of work-related information exchanges between people. Consistent with the model, all reported interactions were symmetrised. The weight of each interaction was calculated based on the reported frequency of the interaction and the estimated impact of that interaction on the design work. The engineering department to which each person was affiliated was used as compositional attribute.

#### 4.1.3 Mapping of process-organisation data

We obtained all 11.742 data logs recording who was working when and for how long in all of the 44 selected activities. Mapping of people to activities was weighted based on the amount of hours spent on the activity and subsequently normalised.

### 4.2 Application and case study results

#### 4.2.1 Characterising the network architectures of activities

Following the proposed framework, for each of the 44 activities, we measured the network size, the network density, and the network compositional diversity (using IQV). Figure 4 shows a graph-based illustration for three of the 44 activities. These three activities were selected to illustrate different combinations of size, density and compositional diversity as well as to show the effect of the weighting of both the interactions between people and the strength of the affiliation to the activity.

- ***Activity A: Flexibility calculation of structural mechanics*** shows a relatively small and dense network where all the participants are from the same department. Only one dense group is distinguishable and two members (P01 and P03) are steering the activity, while P02 only participates incidentally.
  In terms of performance measures, this activity has on average 0.33 revisions per document and compared to original estimates, used ca. 5% fewer hours than originally planned.
- ***Activity B: Definition of buck stays and fixations*** is characterised by a larger and sparser network. Here, unlike Activity A, members differ significantly in their embeddedness in the network. For example, while P05 exchanges information with all the other people in the activity, P08 only exchanges information directly with P05. The activity exhibits relatively low diversity, as all members except one are part of the same department.
  In terms of performance measures, this activity has on average 0.75 revisions per document and compared with original estimates uses almost 50% fewer hours than planned.

- ***Activity C: Evaluation of manufactured designs*** is comparatively a larger and slightly more diverse network. Despite its larger size and higher diversity, the connectivity between its members is stronger than Activity B.
  In terms of performance measures, Activity C has an average of 0 revisions per document and an estimate of 37% hours overrun.

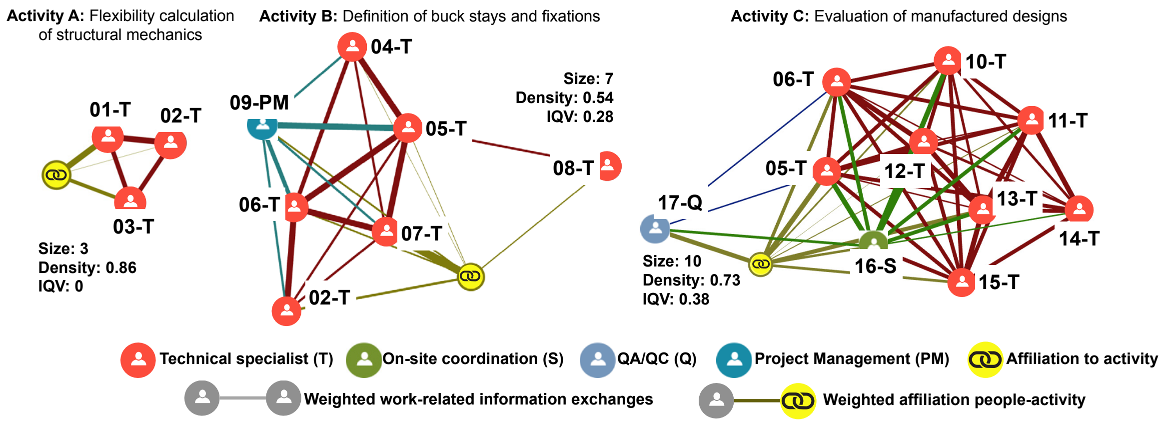


*Figure 4. Three graphical examples of actual activities architectures. The graph layout is weighted and force-directed to represent different intensities of information exchanges. Project members are coloured according to their departmental affiliation.*

Drawing preliminary conclusions about relationships between the network architecture of an activity and its performance solely on a one-by-one examination of each activity (such as the one provided above) is laborious and potentially misleading. We argue that a more robust and scalable approach is required to systematically test such relationships. This is where the second part of our proposed method to identify patterns in activities' architectures via clustering and statistical analysis comes in.

#### 4.2.2 Exploring the relationship between activities' architectures and performance

A two-step clustering analysis was performed to identify groups of activities that share similar architecture configurations and to analyse if those clusters had performance differences. As a result of the clustering (with silhouette measure of cohesion and separation of 0.5), we obtained three statistically distinct clusters. As illustrated in figure 5:

- Cluster #1 contains 61.4% of all activities (27) and is characterised by activities with a large number of people, a density range from low to medium and a low level of heterogeneity. In terms of average document reviews and hours overrun, activities in this cluster show an average performance level.
- Cluster #2 contains 20.5% of all activities (9) and is characterised by activities with a small number of people, high density and low heterogeneity. In terms of document reviews and hours overrun, this cluster has the activities that showed the best performance in the process.
- Cluster #3 contains 18.2% of all activities (8) and is characterised by activities of medium to high density and medium to high heterogeneity. Size-wise, activities in this cluster do not display a distinctive pattern. Given the amount of activities in this cluster, and especially when compared with cluster #2, cluster #3 concentrates a higher number of document reviews than average and has a higher percentage of hours overrun.

In order to examine if there are significant performance differences between the clusters, a one-way ANOVA test was performed. The test results show that in terms of average performance across clusters, there is no statistically significant difference for the average of document revisions or the amount of hours overrun as a percentage. However, a statistically significant difference ($p=0.05$) was indeed found between the standardised nominal amount of hours overrun and the clusters. ***This allows us to confirm that in this case study, the network characteristics of the clusters are associated with a statistically significant difference in the nominal amount of hours overrun.***
Although causation cannot be identified directly through this analysis, the results of this case study indicate that in the analysed process, activities with a low departmental diversity, high network density and a small size outperform other network configurations. Why might this be the case? In this company context, designing a biomass power plant is variant or adaptive design. We may speculate

that in the case of variant design, a homogeneous and small group of well-connected individuals might lead to higher efficiency, as what matters is deep technical expertise and the minimisation of communication barriers and co-ordination efforts. This said, if causality exists, it could also be pointing in the opposite direction, whereby more technically complex activities tend to be organised in a form that includes larger and more diverse groups of people. Further studies are needed to devise definitive causal explanations.

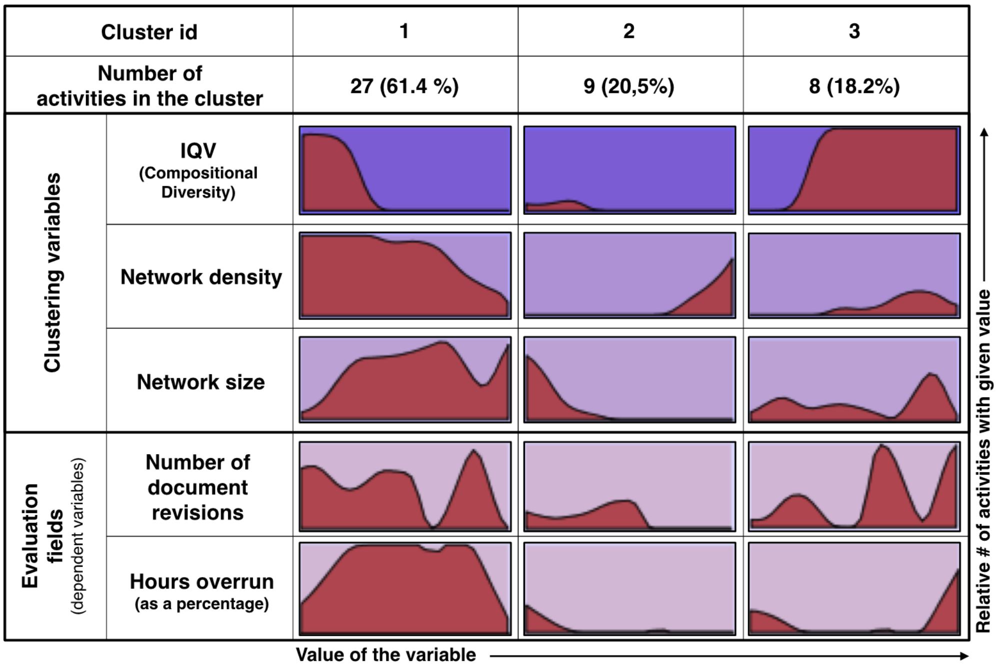


*Figure 5. Graphical characterisation of the three identified clusters. Size, density and diversity metrics of the activity's architectures were used as clustering variables. For each cluster, the relative distribution of the clustering variables is plotted.*

## 5 CONCLUSIONS

To support the design process of large engineering systems, the present paper proposes and tests a framework that characterises the architecture of design activities as organisation networks in a systematic and scalable manner. Activities' architectures are analysed in terms of their structure using network size and density, and in terms of their composition using the Index of Qualitative Variation (IQV) as a measure of compositional diversity. The framework is composed of a flexible conceptual model that can be adapted to fill different industrial and design research needs and a data-driven method to quantify the model and to identify process anomalies and intervention points. Applying the framework to a large engineering design project, this paper showed how the systematic characterisation and data-driven analysis of the architecture of each activity provide actionable insights that increase process overview and reflection.

The framework's novelty lies in:

- The combination of information about the process and organisation architectures of the whole engineering design project to describe the architecture of each activity. This is achieved by leveraging what are nowadays common digital traces, including activity logs and communication systems such as emails.
- The identification and adaptation of a set of methods to quantify and analyse the obtained characterisation. Some of these methods have so far not been used in Engineering Design research, including two-step clustering and the index of qualitative variation.

Implications for design research include:

- The creation of a bridge for follow-on studies connecting whole process architecture models (e.g. Browning & Ramasesh, 2009) and detailed design activity characterisations (e.g. Bucciarelli, 1988). This has been achieved through a network perspective that integrates essential characteristics of the organisation network. This bridge fosters our understanding of the relationship between the design process and the organisation that performs each of the activities.

- The framework provides a new platform to build hypotheses and to test relationships between architecture and performance on the level of each activity and therefore, relationships may already be identified without the necessity of conducting multiple studies of design processes.

Implications for practice include:

- The proposed framework allows supporting the management of engineering design projects through an up-to-date overview of the architecture of each activity. This increases process overview and reflection and enables the systematic identification of best practices and problems that may be caused by or be correlated with the network architecture of activities.

Limitations of this approach are that on its own it cannot distinguish between causation and correlation. Also, the model is blind to the content of work-related information exchanges. Therefore, it does not distinguish between different types of information exchanges between activities.

Future research may expand this framework by integrating the effect of the product architecture, by including additional metrics for architecture and performance, and by controlling for the potential moderating effect that the different activity types (e.g. defined by Sim & Duffy (2003)) may have on the relationships between architecture and performance.


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