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Social Network Analysis of DFAB House: a Demonstrator of Digital Fabrication in Construction

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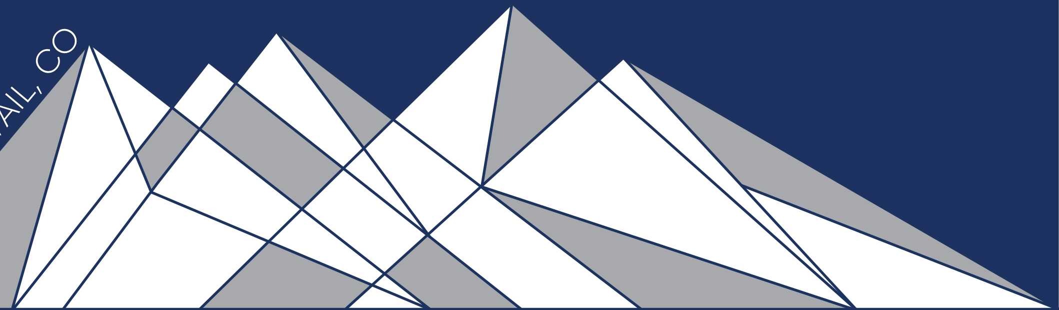

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SOCIAL NETWORK ANALYSIS OF DFAB HOUSE: A DEMONSTRATOR OF DIGITAL FABRICATION IN CONSTRUCTION

ABSTRACT

Digital fabrication technology such as robotic fabrication and 3D printing shows promise to provide customized building components at lower cost while also improving efficiency, reducing waste, and increasing on-site safety. However, the application of digital fabrication in construction is still in its early stages. Digital fabrication differs fundamentally from the conventional means of construction as it combines design and construction into an integrated process through programming languages.

Past research suggests systemic innovations such as digital fabrication will require more integrated and collaborative project ecosystems to succeed. However, few digital fabrication projects have been completed, and little research has quantitatively assessed the emerging network structures of such collaborative project ecosystems for digital fabrication. Important questions remain about what type of project setting, team structure, and project organizational structures are effective when implementing digital fabrication.

This paper looks at the case study of DFAB HOUSE, the first inhabited home planned and constructed predominantly using digital fabrication, to answer these questions. Using Social Network Analysis (SNA), we visualize the network of actors and quantify the network characteristics for the interactions, information exchange, trust and challenge between project participants. From this analysis, we suggest that implementation of digital fabrication benefits from 1) a dynamic, multi-polar organizational structure, 2) strong industry/researcher ties with bi-directional information exchange, and 3) has high levels of interdisciplinary challenge ties that do not correlate with low levels of trust ties. Furthermore, we discuss how a network perspective of project organization can help analyze and communicate the organizational structures at work when implementing novel digital fabrication technologies in an innovative and exploratory construction project. We conclude with suggestions to further study integrated, interdisciplinary project structures that could prove effective for the future adoption of new digital fabrication technologies or other systemic innovations in AEC.

KEYWORDS

digital fabrication, social network analysis, project organization, systemic innovation, DFAB HOUSE

1. INTRODUCTION

Various studies have demonstrated that the Architecture, Engineering, and Construction (AEC) industry is slow at adopting innovations (Winch 2003, Taylor 2004, Hall et al. 2018). The digitization level of the industry is among the lowest of all. As a result, the productivity of the industry has fallen far behind the overall economic productivity. In some countries, construction productivity has even declined since the 1990s (McKinsey&Company 2016; World Economic Forum 2016).

Digital fabrication in architecture shows great potential to improve the productivity of the AEC sector (García de Soto et al. 2018). Digital fabrication differs fundamentally from the conventional means of construction as it combines design and construction into an integrated process through programming languages (Gramazio et al. 2014). Despite its potential, digital fabrication is not yet consistently adopted in the industry for full-scale projects. Instead, new digital fabrication prototypes remain confined to research labs as small-scale demonstrators. Because few full-scale digital fabrication projects exist, it is not yet understood how new technical requirements of digital fabrication might require new organizational structures that differ from those currently found in the AEC sector (Hall 2018).

Recently, the National Center of Competence in Research (NCCR) Digital Fabrication at the Swiss Federal Institute of Technology in Zurich (ETH Zurich) completed the world's first inhabited house that was digitally planned and mostly digitally built through the use of cutting-edge digital fabrication technologies such as 3D printing and robotics. Named the DFAB HOUSE, the project required substantial resources over a period of three years to plan and execute the design and construction. The DFAB HOUSE offers one of the first opportunities to understand the organizational structure of digital fabrication processes in a realized construction project.

Figure 1.1: NEST with DFAB HOUSE (top left). Photo: Roman Keller

The DFAB HOUSE project is characterized by highly integrated processes, both vertically from design to fabrication, and horizontally within interdisciplinary teams. The organization of the project encompasses complex interactions between research and design teams as well as various industry partners. This study seeks to understand these interaction patterns. Since digital fabrication processes differ fundamentally from conventional methods, traditional role definitions and attributes for the project actors such as architects, engineers, or contractors may not be accurate or appropriate. There may also be new roles that do not exist in traditional construction projects. One of the objectives of this study is to understand the roles, attributes, and communications of actors beyond their pre-assigned positions and titles.

To accomplish this, this paper uses social network analysis (SNA) to analyze the project networks of DFAB HOUSE. The use of a network analysis allows the authors to understand how stakeholders collaborate in digital fabrication processes. Through the theoretical lens of digital fabrication, systemic innovation diffusion, and project networks in construction, we first attempt to understand the project management and organizational implications of digital fabrication in design, engineering, and construction. In addition, we unpack how this application of social network analysis helps advance understanding of the mechanisms of systemic innovations such as digital fabrication.

2. THEORETICAL BACKGROUND

2.1 DIGITAL FABRICATION IN CONSTRUCTION

Digital fabrication literally means “data-driven manufacturing.” It is generally understood as a manufacturing process where the tools are controlled by the computer (Gershenfeld 2012). In this process, design and production information is converted into fabrication code that controls machines to complete manufacturing tasks. The last decades have witnessed a boom in productivity in the manufacturing industry brought about by digital fabrication technologies, as digital manufacturing concepts such as Computer Integrated Manufacturing (CIM) have revolutionized production processes and products (Balaguer and Abderrahim 2008).

Digital fabrication is not entirely new to the construction industry. In the 1980s and 1990s, digital fabrication experienced an early boom with the development of specialized robotic systems for building construction. These systems largely aimed at automating formerly manual standard tasks. Most of them were developed in Japan to address the problem of a shrinking workforce in the construction industry (Bechthold 2010). These attempts never found a broader application, in part due to the high degree of standardization they imposed and the genericity of the resulting products (Gramazio et al. 2014; Bonwetsch 2012; Bock 2004).

The introduction of digital design software created new opportunities for digital fabrication. Adapting digital manufacturing technologies already in use in other industries opened up new horizons for digital fabrication in the AEC sector. The use of digital design tools extended the architectural vocabulary with complex and abstract new forms, e.g. topological geometries such as NURBS (Non-uniform rational basis splines). While these types of geometries are hard to produce by conventional means of construction, they are compatible with computer numerically controlled (CNC) fabrication processes (Kolarevic 2001). Digital fabrication technologies also prompted an expansion of architectural design from mere definition of geometry to the design of materialization processes themselves. Computer programming and parametric, constraint-driven design enable direct and precise control of complex material processes. This can lead to entirely new material systems and design expressions (Gramazio et al. 2014).

Several consultant reports identify the potential of digital fabrication technology to transform the construction industry through its potential to improve efficiency, reduce construction waste, improve on-site safety, and provide customized building components at lower cost (McKinsey&Company 2016; World Economic Forum 2016). However, the development of digital fabrication in construction is still in its early stages. Research results remain largely confined to prototypes and demonstrators. Industry adoption is currently very limited, and digital fabrication is not yet deployed at scale in the industry.

2.2 INNOVATION DIFFUSION IN THE CONSTRUCTION INDUSTRY

Past research indicates that the adoption of digital fabrication technologies will be difficult and slow-moving in the AEC sector (Taylor 2004). This difficulty has been tied to the industry's vertical, horizontal and longitudinal fragmentation (Howard et al. 1989, Hall et al. 2014). Digital fabrication can be categorized as a systemic innovation. The technologies cut across traditional discipline and supply chain boundaries and require changes to the system integration of the project. Systemic innovations cross professional and trade specializations, redefine how work is done, and break craft administration standards (Taylor 2004). Past studies have found that systemic innovations are three times less likely to be adopted on AEC projects in comparison to modular or incremental innovations that fit within existing discipline and supply chain boundaries (Sheffer 2011, Katila et al 2018). This is despite evidence that systemic innovations often offer superior system-wide gains in budget, schedule, and energy performance (Hall and Lehtinen 2015).

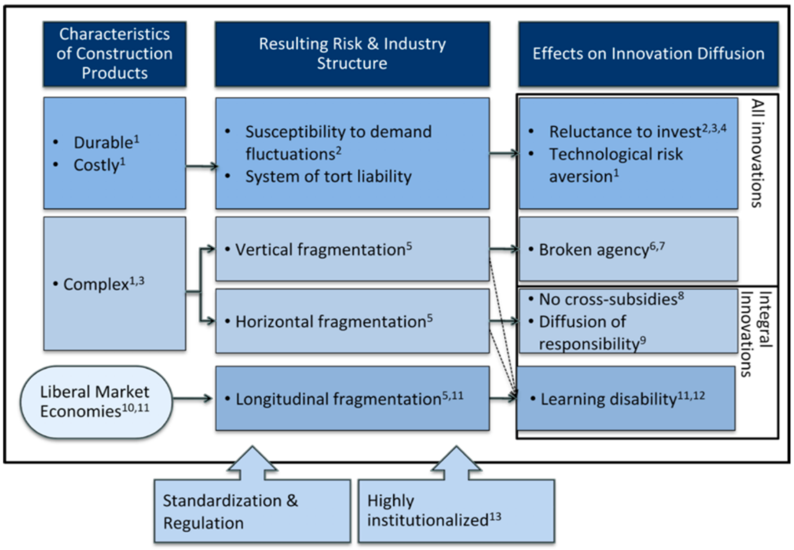

Figure 2.1 - Framework for understanding structural barriers to innovation in construction (Sheffer 2011).

The adoption of digital fabrication technologies will be resisted by an AEC sector characterized by extreme fragmentation, technological risk aversion, a culture of low cost competitive bidding, and broken agency in decision making (Levitt 2007; Sheffer 2011; Hall et al. 2018). Systemic Innovation in AEC cannot be accomplished by a single firm. It is highly influenced by the inter-organizational nature of the industry (Taylor 2006). The previous interconnected product and process investments result in a network of interdependent solutions. It is difficult to replace or combine with any solution that has been developed outside this network (Bygballe et al. 2015). As a project organization is a form of socio-technical system (Sackey et al. 2015), systemic innovation adoption is a negotiation process among the multiple actors and firms involved (Winch 1998). For this reason, the slow rate of systemic innovation adoption in construction is highly influenced by the industry structure and project organization.

2.3 NETWORKS IN CONSTRUCTION PROJECT ORGANIZATION

To understand social phenomena through the lens of networks is a well-established research approach in social sciences. Social networks emphasize the linkages between a defined set of social units whose connections with each other influence their actions (Mitchell 1969). Social networks express a social environment in patterns of relationships between interacting social units, allowing observation of the impact of social structures on various social phenomena (Wasserman and Faust 1994).

Project organizations are the core principle on which AEC operates. Organizations are, by nature, social networks having a relatively stable structure of social linkages over a certain period of time (Tichy et al. 1979). Besides the formal or prescribed relationship structure in an organization, informal "emergent" relationships are an important component shaping organizations (Eccles and Nohria 1992). As Nohria and Eccles (1992) stated, "Networks constrain actions and in turn are shaped by them". Looking at interaction processes can therefore help understand both an organization and the actions of individuals within it.

Similar to a social community, an engineering project organization has multi-level networks. These networks are comprised of formal relationships, mainly the contract relations and official project positions, and informal relationships, which are spontaneous interactions between stakeholders necessary in the project's execution (Chinowsky and Taylor 2012). Studying these networks can complement traditional research tools in the construction project management domain. It can reveal interaction patterns between stakeholders that cannot be reflected through explicit relations in contracts and organizational charts (Pryke 2012).

2.4 SUMMARY OF LITERATURE

Although digital fabrication technologies are not entirely new to the AEC sector, the industry has benefited little from them to date. The transformation brought about by the digitalization of production in other industries did not occur in the AEC sector. The recent development of digital fabrication technologies for construction has shown a promising potential for change (Bechthold 2010; Kolarevic 2001; Gramazio et al. 2014; McKinsey&Company 2016; World Economic Forum 2016). However, the adoption of digital fabrication in the industry has been difficult and slow moving. In theory, because digital fabrication is a systemic innovation, it will require changes to the project organization structures and roles for project participants (Taylor and Levitt 2004, Sheffer 2011, Hall et al. 2014). Until now, little research has studied the specific implications of digital fabrication technologies for the management and organization of projects in the AEC sector. This is in large part because – to our knowledge - there are no example projects that have embraced full-scale digital fabrication from design through construction.

By drawing on one of the first full-scale digital fabrication projects completed, we have the opportunity to answer two research questions in this area. First, how can we use a theory of networks to understand the project management and organizational implications of digital fabrication in design, engineering, and construction? Second, what are the benefits of applying social network analysis to understand the mechanisms of systemic innovations such as digital fabrication?

3. RESEARCH DESIGN

In order to answer the aforementioned research questions, we specifically draw from theories of project networks in construction. We conduct a social network analysis on a single case study — the DFAB HOUSE. This research looks at forms of interaction, information exchange, and the importance of trust and challenge in an interdisciplinary project organization. Specifically, it looks at the potential of studying social networks in order to comprehend, learn from, and communicate complex levels of relations within project organizations. This approach aims at understanding what type of project setting, team structure, and project organizational structure are at work when implementing systemic innovation across discipline boundaries in design, engineering and construction, with particular focus on new digital fabrication technologies in the AEC sector.

3.1 SOCIAL NETWORK ANALYSIS

We chose Social Network Analysis (SNA) as an appropriate method to pursue this study. SNA has been shown to be an effective tool in studying organizational structure (Eccles and Nohria 1992; Pryke 2012), and has been used in the engineering project management domain (Chinowsky and Taylor 2012). SNA has the advantage of being able to visualize and model complex multi-level project networks and especially the emergent informal relationships that reveal the actual collaboration mechanisms of an organization (Eccles and Nohria 1992; Zheng et al. 2016).

SNA visualizes patterns and structures of interactions between actors in a graphical format, using nodes to represent actors and edges to represent their connections. The translation of qualitative social relationships into mathematical models, based on graph and probability theories, makes the quantitative analysis of social interactions possible (Wasserman and Faust 1994). It is particularly effective in modeling non-linear, complex, and interactive processes (Pryke 2012).

3.1.1 Social Network Fundamentals

This section briefly introduces the key concepts and terminology of network properties used to assess the social networks in this study.

- Node

Node is a concept from graph theory. The points used in a graph to represent the actors in a social network model are called nodes (Wasserman and Faust 1994).

- Edge

Edges are the lines connecting the points in a graph that represent the ties between the actors in a social network model (Wasserman and Faust 1994).

- Degree

The degree of a node is “the number of nodes adjacent to it”. It indicates how many direct ties an actor has (Wasserman and Faust 1994).

- Weight

Weight is the intensity, strength, or capacity associated to the tie between two actors in a social network model (Barrat et al. 2004). In this study, the weights of the edges represent either the frequency of interaction between stakeholders or the degree of challenge or trust.

- Weighted Degree

The weighted degree of a node is the sum of the weights of all the edges of the node. It adds the information about the weight of the edges to the measure of degree (Barrat et al. 2007).

- Centrality

Centrality is a measure of the prominence or importance of an actor in the social network. Wasserman and Faust (1994) defined prominent actors as “those that are extensively involved in relationships with others actors”. There are several ways to define the centrality of an actor (Wasserman and Faust 1994). Two measures used in this study are *degree centrality* and *betweenness centrality*.

An actor’s degree centrality is equal to the node’s degree. With this definition, the most central actors are the ones with the most ties to other actors, or the highest nodal degree (Wasserman and Faust 1994). In this study, the concept of degree centrality is expanded to weighted degree. Taking into consideration the intensity of ties, weighted degree centrality measures the centrality of an actor with reference to the weighted degree.

An actor’s betweenness centrality is defined as the number of shortest paths between all other actors that also include this actor. A higher the betweenness centrality can indicate a higher level of control over the interactions of other actors in the network (Wasserman and Faust 1994). This study uses Brandes’s algorithm for measuring betweenness centrality (Brandes 2001).

3.1.2 SNA Concepts in AEC Project Organization Research

This section introduces key concepts of social network analysis according to definitions by Wasserman and Faust (1994) in relation to the research setting of the study.

- Actor

Actors are social entities linked together through certain kinds of connections in a social network. Actors can be individuals, corporates, or collective social units (Wasserman and Faust 1994). In this study, actors are defined as the individual stakeholders of the project DFAB HOUSE.

- Relation

A relation is the sum of a certain type of ties that link actors to each other. Building on the social network model of construction developed by Chinowsky et al. (2008), this study measures six kinds of relations for the defined group of actors:

1. *Communication*

   The communication network measures the non-directional communication connections between actors. It reveals the general interaction patterns within the project teams and reflects the informal structure of the project organization (Chinowsky et al. 2008).

2. *Information exchange*

   The information exchange network measures the directed, task-specific information flow between project actors. In one direction, an individual gives out information to others so that they can do their work, and, in the other direction, the individual receives information from others to complete his/her own work. These networks may vary with tasks. However, they reflect how information is transferred in both directions to complete tasks within the project organization (Chinowsky et al. 2008).

3. *Problem-solving*

   The problem-solving network reflects whom people turn to for help or advice when they encounter a problem at work. It captures the problem-solving mechanisms within the project organization, which are especially crucial for an innovative project like DFAB House.

4. *Innovation*

   This network shows whom people talk to about new solutions or ideas related to the project. It measures how ideas and innovations diffuse and evolve within the project network.

5. *Challenge*

   The challenge network measures the degree of challenge between project actors when working together. This study focuses on the challenges caused due to a professional background. Professional background includes knowledge, routines, and expectations at a professional level. This does not include personality differences or interpersonal conflict. The challenge network shows where in the project organization actors with various backgrounds may encounter difficulties in collaborating.

6. Trust

The trust relationship measures the degree of trust between project actors. Research has shown that the level of trust within a project network can influence the ability of a project team to achieve high performance that goes beyond mere completion of tasks (Chinowsky et al. 2008). This study focuses on trust based on professional interactions but not on personal interactions.

3.2 CASE STUDY: DFAB HOUSE

DFAB HOUSE is an experimental construction project realized with digital fabrication technologies developed by the Swiss National Center of Competence (NCCR) Digital Fabrication, a Swiss national research initiative regarded one of the world's leading research groups in digital fabrication in the AEC field[1]. DFAB HOUSE is part of NEST, a modular research and innovation building platform at Empa, the Swiss Federal Laboratories for Materials Science and Technology.

DFAB HOUSE is a comprehensive technology demonstrator by the NCCR Digital Fabrication, which takes a leading position in the global research field of digital fabrication. As such, DFAB HOUSE is a unique project to get insight into the complete chain of digital processes in construction, from design to fabrication. However, the DFAB HOUSE is not only a demonstrator of advanced technologies. It is conceived to be a full-featured, inhabitable building unit that meets both building codes and industry environment, aiming at bringing digital fabrication technologies closer to the market. As a first-time application of several fundamentally new technologies, DFAB HOUSE is innovative not only from the technical but also from the organizational aspect. During its realization, new workflows were developed, new processes were created, and new collaboration mechanisms have emerged. It presents an opportunity to understand the organizational mechanism of digital fabrication processes in a realistic setting.

DFAB HOUSE is a non-commercial experimental project. Its structure was set up to facilitate the demonstration of research results. A formal contractual structure exists between the owner, a general planner and individual execution contractors. The exploratory nature of the project also required a number of less formal and individual agreements to provide room for interdisciplinary problem solving based on the challenges at hand. Informal networks therefore reflect the project's collaboration mechanisms and roles better than formal ones. This research attempts to quantitatively visualize and assess these informal structures, which are typically difficult to assess.

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[1] The National Centre of Competence in Research (NCCR) Digital Fabrication is Switzerland's initiative to lead the development and integration of digital technologies within the field of architecture. It is funded by the Swiss National Science Foundation (www.dfab.ch, accessed March 18 2019). DFAB House was implemented by the NCCR Digital Fabrication in collaboration with 40 industry partners (www.dfabhouse.ch, accessed March 18 2019).

3.2.1 DFAB HOUSE Innovation Objects

The DFAB HOUSE project combines six fundamentally new digital fabrication technologies in a single building. These applications, labeled ”Innovation Objects” or IOs, are based on fundamental research at the NCCR Digital Fabrication. They were developed by interdisciplinary consortia composed of research and industry partners.[2] This section provides an overview of the technologies used in DFAB HOUSE.

1. *In situ Fabricator*

   The In situ Fabricator (IF) is a versatile, mobile, on-site construction robot. It is equipped with sensing and feedback systems to operate autonomously in the unstructured environment of construction sites (Lussi et al. 2018). The IF is a versatile tool for on-site digital fabrication in construction. The main disciplines involved in this IO are robotics, industrial engineering, and control systems and computer science.

2. *Mesh Mould*

   Mesh Mould is a robotic, formwork-free fabrication process for non-standard cast-in-place concrete structures. A dense rebar mesh fabricated by a robot functions both as a lost formwork and as reinforcement. Besides automation of rebar fabrication it aims at free-form geometry, structural optimization and waste reduction (Hack et al. 2018). Disciplines involved in research and planning are architecture, structural engineering, material science, robotics, and industrial engineering. The main construction trade involved is concrete construction.

3. *Smart Slab*

   Smart Slab is a prefabricated concrete slab introducing large-scale 3D sand print technology as formwork. A generative design software takes into consideration structural optimization, free-form design, and the integration of installation systems (Meibodi et al. 2018). Disciplines involved in research and planning are architecture and digital design, material science, additive manufacturing, and structural engineering. Construction trades involved are concrete prefabrication, post-tensioning, CNC timber manufacturing, and electrical and sprinkler systems. Other manufacturing trades involved are industrial 3D printing and polymer manufacturing.

4. *Smart Dynamic Casting*

   Smart Dynamic Casting (SDC) is an automated concrete slip-forming process. It uses an adaptable, reusable moving formwork. This eliminates the need for customized disposable formwork for individualized, non-standardized prefabricated concrete elements. In DFAB HOUSE, SDC was used to produce structurally optimized concrete façade mullions (Lloret Fritschi et al. 2018). Disciplines involved in this IO are architecture, structural engineering, materials science, and industrial engineering. Construction trades are concrete prefabrication and facade manufacturing.

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[2] “About DFAB HOUSE”, DFAB HOUSE Website. Accessed March 18 2019. http://dfabhouse.ch/dfab-house

5. *Spatial Timber Assemblies*

   Spatial Timber Assemblies is a robotic prefabrication process for timber frame systems. A fabrication-aware design code generates fabrication information for a multi-robotic fabrication set-up. Collaborating robots then prefabricate customized building modules. The process achieves a high degree of automation and allows for bespoke prefabrication, structural optimization and waste reduction. It was used to fabricate a two-story modular residential portion of the DFAB HOUSE. (Thoma et al. 2019). Disciplines involved are architecture, structural engineering, robotics and control systems. The main construction trade is modular timber prefabrication.

6. *Lightweight translucent façade*

   A lightweight translucent membrane façade system was developed for integration in the Spatial Timber Assemblies part of the project. Disciplines involved are architecture, façade engineering, materials science, and building physics. Construction trades include tensile facade manufacturing and thermal insulation technology.

4. RESEARCH METHODOLOGY

To analyze the DFAB HOUSE using SNA, we performed three methodological steps. The first step of the study is the identification of the stakeholders constituting the project network. For this task, a global project address was list provided by the project management. This list also contained information on the classification as stakeholders, e.g. as researchers, consultants, industry partners, etc. Further stakeholders were identified through participants as part of the survey to complete the stakeholder map.

The second step of the study is to collect data for the network from each actor on the stakeholder map. For this purpose, we conducted an online survey among all stakeholders. The survey questions focused on understanding different kinds of relationships among the actors, as further described in Section 4.4.

Finally, the results collected from the survey were processed in Gephi, an open source network analysis and visualization software, to build the social network models. We then analyzed these networks to find out how the stakeholders collaborate and what characterizes their collaboration mechanisms.

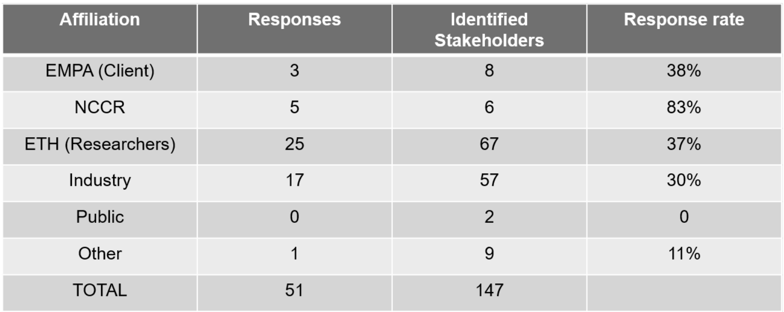
4.1 IDENTIFICATION OF STAKEHOLDERS

The boundary of the survey was the project participants of DFAB HOUSE. We identified 147 project participants through the address list provided by project management and information available on the project homepage. Additional participants identified through the survey were also invited to take the survey. The available data allowed us to identify six groups of stakeholders:

- The Client/Owner: nine stakeholders affiliated with Empa.
- NCCR management: six stakeholders including two project managers/architects and four staff of NCCR Digital Fabrication responsible for general management

of the NCCR, knowledge and technology transfer, and external and internal communication.

- NCCR researchers and technicians: 67 stakeholders, including Principal Investigators and researchers on the postdoctoral, PhD and assistant levels as well as technical staff administering digital fabrication systems.
- Industry partners. 57 stakeholders, affiliated with: industry supporting at the single research project level (6); partners in R&D, upscaling and execution of the IOs for DFAB HOUSE (25); specialist planners and consultants on the DFAB HOUSE project (14); and execution contractors (18).
- Public authority. Responsible reviewers from the building and fire safety departments (2).
- Stakeholders with miscellaneous external affiliations (9).



Affiliation	Responses	Identified Stakeholders	Response rate
EMPA (Client)	3	8	38%
NCCR	5	6	83%
ETH (Researchers)	25	67	37%
Industry	17	57	30%
Public	0	2	0
Other	1	9	11%
TOTAL	51	147	

Table 4.1.: Project stakeholders and response rates

4.2 DATA COLLECTION

This study used an online-survey method to gather the network data from project actors. The survey is the most common data collection method used in social network analysis, especially when actors are people (Wasserman and Faust 1994). We used the online survey platform Qualtrics to distribute the survey to all identified project participants via email.

The survey focused on understanding interactions between project actors in the project network at different levels and from multiple perspectives. The relations it measured are based on the social network model of construction developed by Chinowsky et al. (2008), as described in Section 3.1.2. The survey addresses both the exchange of information and knowledge among actors, referred to as *Mechanics* in the model; and the social factors, referred to as *Dynamics* in the model, with focus on social aspects that affect the performance of the project.

The survey consisted of two parts. The first part asked respondents to share their basic background information. Besides personal information like gender, language, educational background, and affiliation, respondents were asked to provide background information related to their participation in the project, such as which phases of the project they were involved in and which Innovation Objects they worked on.

The second part asks questions about the respondent's interactions with other actors during planning and execution of the project. This part of the survey was only displayed to those who were involved in the planning and/or execution phases. First, this part of the survey asked to list up to 30 actors with whom they had project related interactions during this time. This was followed up by seven questions asking to rate six types of relations, with the actors they had listed: frequency of direct specific communication related to the project; frequency of information exchange; mutual support in problem solving; frequency of discussing new ideas and innovation; degree of challenge based on different professional backgrounds; and degree of trust (see Table 4.2).

Relationship	Question	Scale	
Specific communication	How often do you have specific communications (face to face, on the phone, via email etc.) with following people about project-related issues?	5 4 3 2 1 0	**Daily** At least once per day **Frequently** Several times per week **Weekly** 1-2 times per week **Infrequently** Less than once a week **Rarely** Less than once a month **Never**
Information exchange	How often do you RECEIVE information from following people that is necessary for you to complete your project-related work ?		
	How often do you GIVE information to them that is necessary for them to complete their project-related work?		
Help and advice	How often do you typically turn to following people for help or advice in solving problems related to the project?		
Innovation	How often do you talk about new solutions or new ideas related to the project with following people?		
Challenge	Please rate the degree of challenge to work with following people on the project due to PROFESSIONAL BACKGROUND. (Professional background is meant to include knowledge, routines, and expectations at a professional level, for example, this might include differing opinions between disciplines regarding work routines discipline-specific knowledge, and/or discipline criteria to evaluate successful research. This would NOT include personality differences or interpersonal conflict.)	1 2 3 4 5 0	No challenge Little challenge Moderate challenge Above average challenge Strong challenge Unknown/No opinion
Trust	How much do you trust following people to take actions that are mutually beneficial to you and them based on your PROFESSIONAL INTERACTIONS with this person?	1 2 3 4 5 0	No trust Little trust Moderate trust Above average trust Strong trust Unknown/No opinion

Table 4.2.: Survey questions and weighting scales

The total response rate was 51 out of 147, or 34.7%. Out of 51 responses, only 37 answered all questions, resulting in a fully complete survey response rate of 25%.

4.3 SOCIAL NETWORK REPRESENTATION MODELS

With the data collected through the survey, we generated social networks for each of the six relations stated in section 4.3, using the social network analysis software Gephi. In these six network graphs, the nodes represent stakeholders, while the edges represent each of the six relationships stated in section 3.1.2 respectively. The weight of the edge represents either the frequency of interaction or the degree of challenge or trust. Table 4.2 shows the scales used to express frequency of interaction and the degree of challenge or trust in the weighting of the edges. The edges are undirected if the relationship represented is non-directional and directed if the relationship represented is directional. The data from the two questions in the survey enquiring about "giving" and "receiving" information was combined in the Information

Exchange network with directed edges from those giving information to those receiving information, indicating whether information flows in one or both directions.

The social networks of specific communication, information exchange, problem solving and innovation are laid out using the force-based algorithm “Force Atlas” in Gephi. The structure of the challenge and trust networks are visualized with the circular layout provided by Gephi, with the nodes ordered by professional groups.

5. FINDINGS

Here we present findings related to specific communication, information exchange, challenge and trust.

5.1 SPECIFIC COMMUNICATION

The Communication network on specific project related issues shows a number of interdisciplinary clusters correlating with the different Innovation Objects or groups of similar IOs (Fig. 5.1). Specifically, Cluster II corresponds to IO *Smart Slab*, Cluster III to IO *Spatial Timber Assemblies*, and Cluster IV to IOs *In situ Fabricator / Mesh Mould* and *Smart Dynamic Casting* (see description of IOs in Chapter 3.2.1). All clusters contain researchers and industry partners. These clusters are multi-polar and highly connected. In each cluster a group of researchers shows the highest degree centrality. Information flows are not focused on one single actor but show direct information flows occurring between all actors within these groups. In addition to these IO clusters, the General Planner together with hired planners and execution contractors and the client forms another distinct cluster in which the GP Project Manager assumes a central role (Cluster IV). However, the network also shows many connections between these clusters, indicating communication between the IO clusters as well as the GP/execution cluster.

The center of the network is formed mainly by the management and communication staff of NCCR (Cluster I) and NCCR Management/Communication (Cluster VI). The Project Manager General Planning, the NCCR Lead Architect/PM and the Project Architect are the actors with the highest degree centrality as well as weighted degree centrality in the Communication network. This cluster shows a high degree of embeddedness, as it has strong ties to all surrounding clusters, which also have strong ties to each other. While these actors facilitate the most communication, information does not flow exclusively through them. There are also alternative, direct paths of communication between the surrounding network clusters.

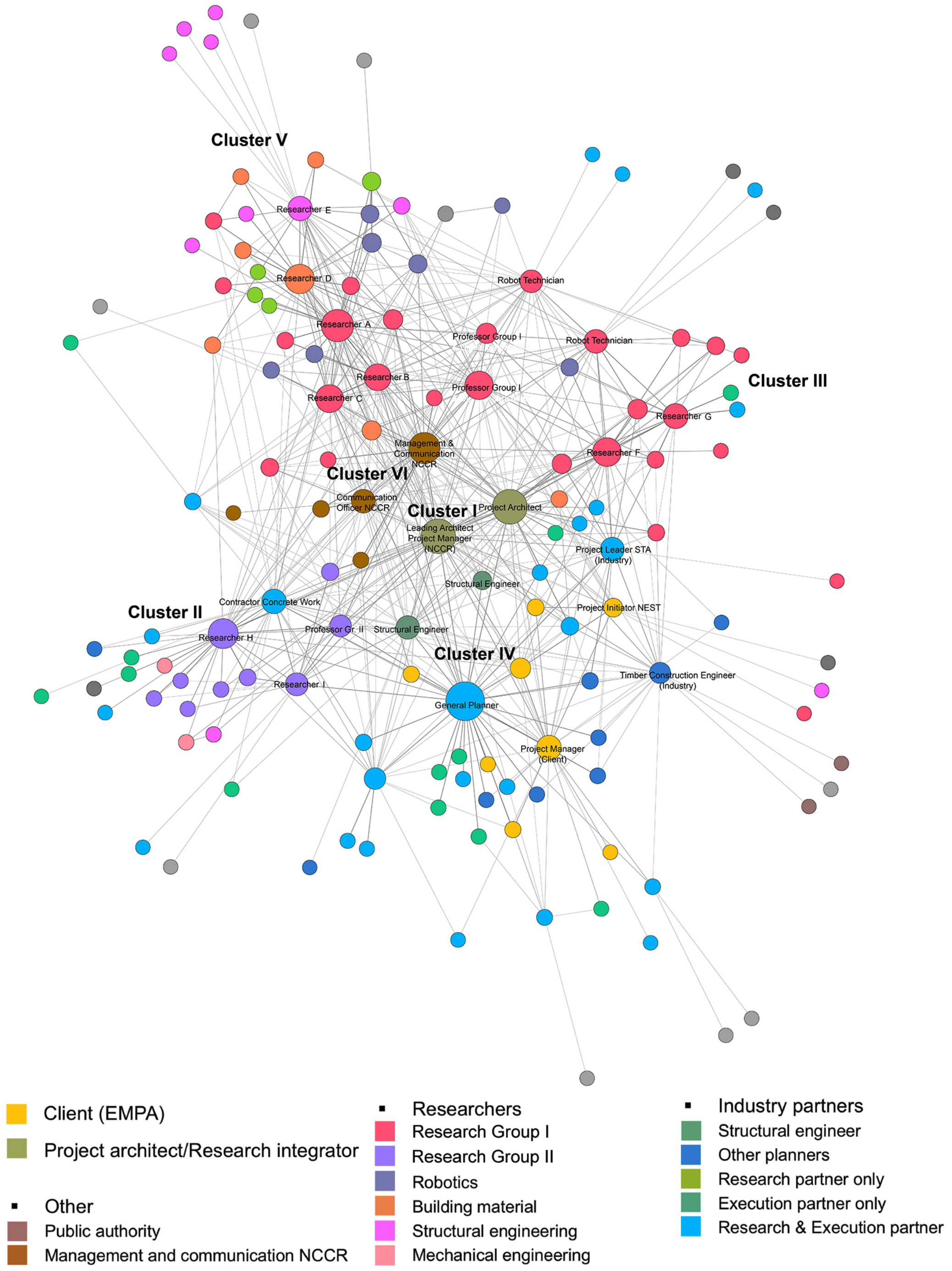


Figure 5.1.: Specific Communication Network with clusters

5.2 INFORMATION EXCHANGE

The Information Exchange network shows communication patterns between communities of practice. In this network, information exchange among researchers and information exchange between industry partners form two clearly discernible communities. Both have a strong pattern of information exchange within them.

The graph showing information exchange between industry partners and researchers identifies the industry partners who are in direct exchange with research. This includes some (but not all) actors from the industry partner community, indicating those who contribute to both research and execution. There are also partners who are exclusively communicating with researchers in their role as contributor to research but not to execution of the project.

Ties between the NCCR project leaders with both industry and research in this network reinforce the ties seen between research and industry. They display information exchange between these two groups going through the NCCR project management (Fig. 5.2).

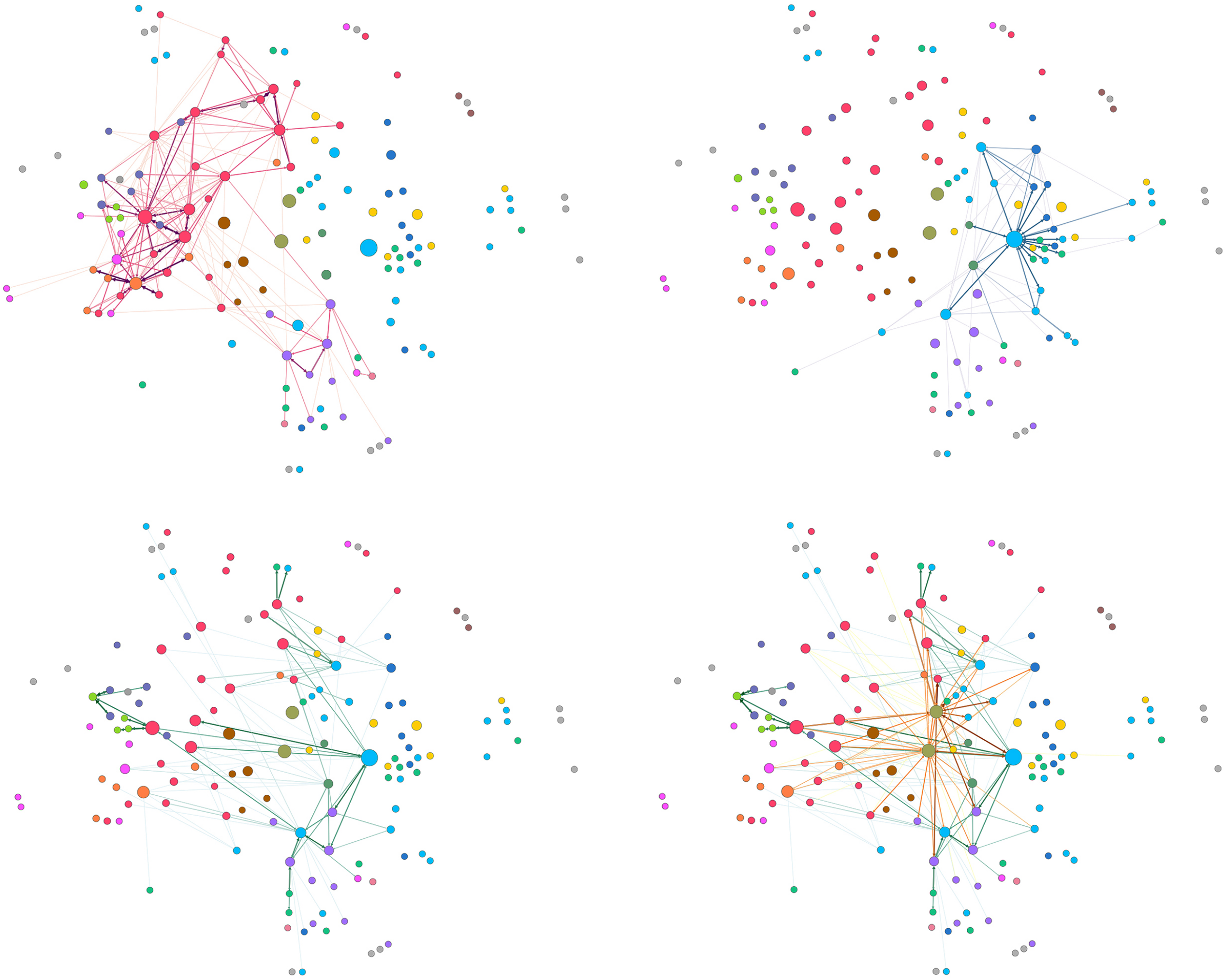


Figure 5.2: Information Exchange between researchers (top left); Information exchange between industry partners (top right); Information exchange between industry partners and researchers (bottom left); Information exchange between NCCR project leaders, industry partners and researchers (bottom right).

The overall Information Exchange network show small information asymmetry. A comparison of the nodal degrees in the network models for information inflow and outflow shows no obvious asymmetry between information regularly received and given by most actors (Fig. 5.3). To illustrate this further, Tables 5.4 show the weighted in-degree vs. the weighted out-degree of the ten most central actors in this network. This suggests that the project network largely relies on bidirectional rather than one-directional information flows.

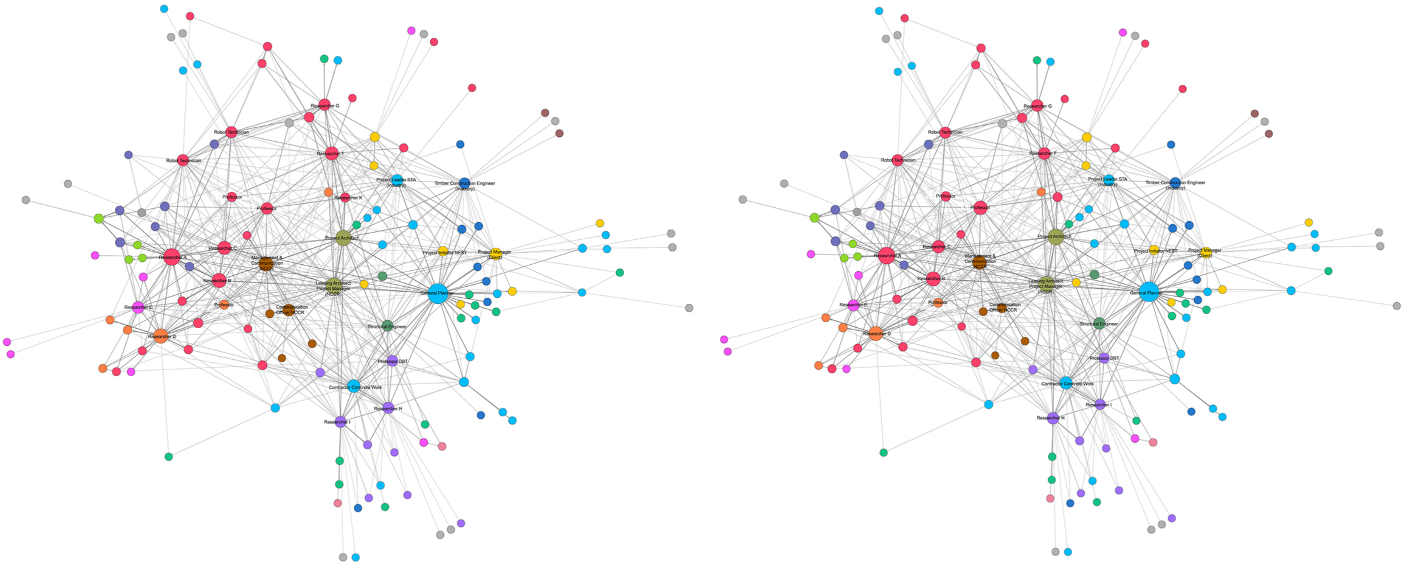


Figure 5.3: Information Exchange; Information inflow (l.) and outflow (l.)

Actor	Weighted In-Degree
General Planner	122.0
Researcher A	89.5
Leading Architect, Project Manager (NCCR)	81.5
Project Architect	78.0
Researcher D	68.5
Researcher B	65.5
Management and Communication NCCR	65.0
Researcher F	56.5
Researcher C	56.5
Contractor Concrete Work	51.5

Information flow: Actors with 10 highest weighted in-degree in descending order

Actor	Weighted Out-Degree
General Planner	122.5
Researcher A	92.5
Project Architect	84.0
Leading Architect, Project Manager (NCCR)	78.5
Researcher B	67.0
Researcher D	66.5
Management and Communication NCCR	63.0
Professor Research Group I	59.5
Contractor Concrete Work	51.0
Researcher C	50.5

Information flow: Actors with 10 highest weighted out-degree in descending order

Table 5.4: Information Exchange, top ten ranking actors in weighted in-degree (left) and weighted out-degree (right)

5.3 CHALLENGE AND TRUST

The Challenge and Trust networks show bilateral relationships between all network actors. The Challenge network graph shows thigh levels of challenge occurring both between different research fields and between researchers and industry partners. There is little challenge reported within each research field or between industry partners. The Trust network is shown in the same format (Fig. 5.5). Table 5.5 shows all bilateral relationships in which the respondent ranked the challenge due to professional background as 5, the highest level in the ranking. For these relationships, it shows the corresponding trust level reported by the same respondent. While there are some cases where high challenge corresponds with low trust, there appears to be no strong correlation.

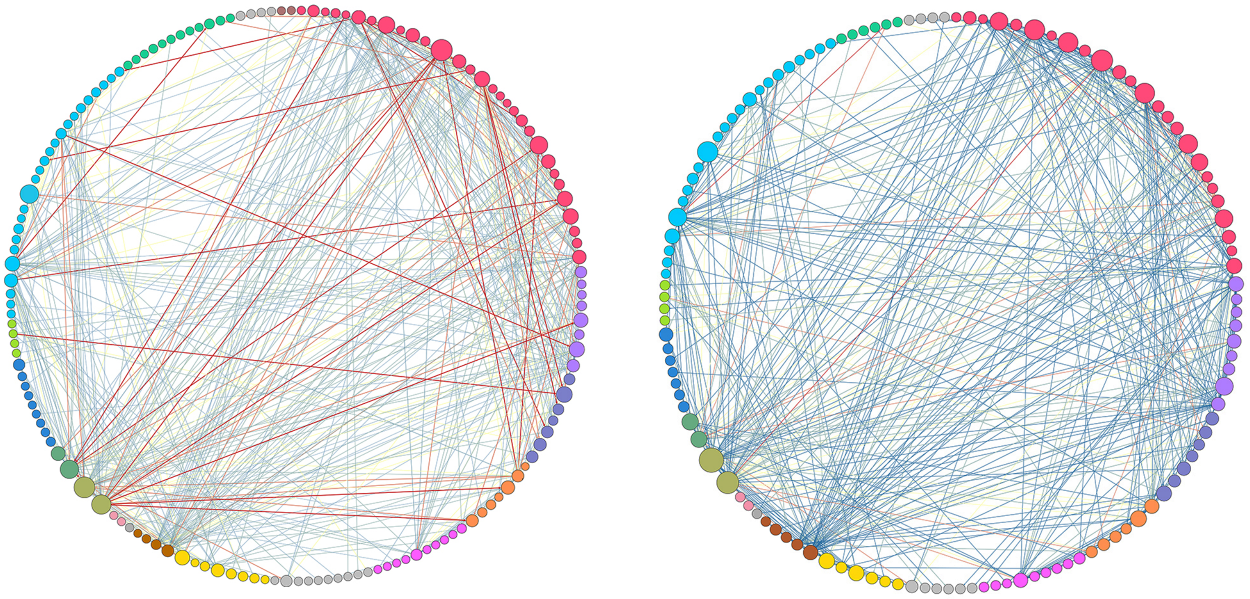
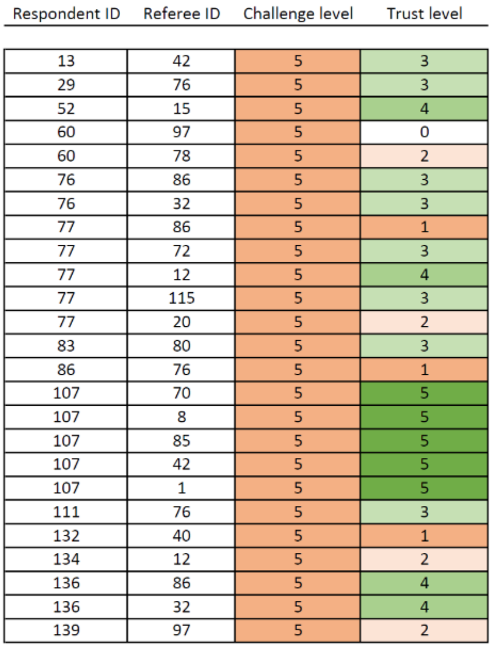


Figure 5.5: Challenge (l.) and Trust (r.) networks



Respondent ID	Referee ID	Challenge level	Trust level
13	42	5	3
29	76	5	3
52	15	5	4
60	97	5	0
60	78	5	2
76	86	5	3
76	32	5	3
77	86	5	1
77	72	5	3
77	12	5	4
77	115	5	3
77	20	5	2
83	80	5	3
86	76	5	1
107	70	5	5
107	8	5	5
107	85	5	5
107	42	5	5
107	1	5	5
111	76	5	3
132	40	5	1
134	12	5	2
136	86	5	4
136	32	5	4
139	97	5	2

Table 5.6: Correlation of challenge and trust for the highest reported challenge level

6. DISCUSSION

6.1 ORGANIZING FOR DIGITAL FABRICATION

Our first research question was how we can use a theory of networks to understand the project management and organizational implications of digital fabrication in design, engineering, and construction. The networks created from data collected about the DFAB HOUSE process give us insight into the emergent structures formed during the implementation of digital fabrication technologies in a construction project. This section discusses three findings from the study that indicate potential forms of integrated project structures required to implement digital fabrication processes.

6.1.1 Dynamic, multi-polar network structure

The communication network suggests an iterative and dynamic project setting. There are high levels of communication *within* clusters, but certain actors also assume key roles in communication *between* these clusters. These actors play an important role within their specific cluster but also act as agents in a multi-polar communication network bridging between the clusters. Their position in the network suggests that the dynamic network allows certain actors to become facilitators of communication between disciplines, improving collaboration and knowledge exchange within the project network.

Management for innovation in digital fabrication relies on many ties between many different actors. This underscores the importance of communication across discipline boundaries for the implementation of this systemic innovation. Specific information exchange happens within the dense research clusters around each IO where the exchange of discipline specific knowledge across the consortium lies at the heart of the development process.

Information exchange within these clusters is complemented by ties between the clusters where certain actors play a special role. These actors either are researchers and industry partners whose knowledge is relevant for multiple IOs, or leading members of IO teams whose roll it is to coordinate across IO boundaries. They are integrators on the project level as well as on the IO level.

The NCCR architects and project managers are also integrators at the project level. They have the highest weighted degree in the network, and their ties show that specific information between all clusters is exchanged through them. Whilst this is usually the case in construction project organizations, it is less typical to find the information flows through them reinforced by direct ties between the different clusters. This doubling of ties forms triads between many pairs of actors in different clusters and a project manager. This type of network structure reinforces trust and indicates a stable project network.

6.1.2 Strong industry/researcher ties with bi-directional information exchange

The information exchange demonstrates many exchanges between researchers and industry partners. It also seems digital fabrication innovation requires bi-directional information flow between project participants.

These observed ties between research and industry and the mutual information flows are crucial in digital fabrication innovation because a high level of horizontal as well as vertical integration is necessary to implement digital fabrication at scale. Horizontal integration is apparent in the information flow between researchers of different backgrounds and from different fields as well as between researchers and industry partners involved in research and development. Digital fabrication is a systemic innovation integrating highly interdisciplinary knowledge and therefore relies on a high level of horizontal integration. Vertical integration shows in information flows between actors involved in research and industry partners on the technical planning and execution side. Digital fabrication requires a high level of awareness of fabrication parameters and constraints in upstream project development, while digital code produced in the planning stages also directly drives the fabrication process. Therefore, vertical integration is also crucial for the implementation of digital fabrication.

6.1.3 Challenge and Trust Correlation

Work in interdisciplinary settings necessarily leads to communication challenges when exchanging information across discipline and institutional boundaries. Consequently, some actors reported a high degree of challenge when working with other actors from different backgrounds. However, this type of challenge does not always correlate with a low level of trust. From this finding we draw the preliminary conclusion that the challenges inherent in interdisciplinary communication are not necessarily a negative indication for a project organization and could potentially be overcome, allowing project actors to develop valuable communication skills over time. Further study using data on the development of trust and challenge levels throughout the duration of a project would be required to substantiate this thesis.

6.2 BENEFITS OF NETWORK BASED APPROACH

Our second research question inquires about the benefits of applying social network analysis to understand the mechanisms of systemic innovation and particularly digital fabrication. Applying SNA as a method to study a complex and innovative project has highlighted two particularly powerful concepts which we lay out in this section.

6.2.1 Organizational knowledge generation

Knowledge generated on complex construction projects is usually unevenly distributed, with key experiences owned only by a small group of key individuals. Without establishing quantitative data on the project, this knowledge typically remains fragmented and dissipates when key stakeholders move on to new projects or other organizations. Experience and knowledge generated collectively through the interaction patterns of a project therefore cannot be recorded and passed on to future projects. However, such knowledge would be essential in overcoming the industry’s vertical, horizontal and longitudinal fragmentation.

Studying projects through the lens of network analysis opens up possibilities to document the dynamics of a project network. This knowledge then becomes accessible within a project team, or beyond project boundaries within a firm or among collaborating firms. Quantitative network data collected during a project can be a valuable resource for decision-making when building new project teams. General metrics of the network such as information exchange and challenge in interdisciplinary settings can provide an underlying framework when analyzing the performance of a project. For example, being able to tie a delay to week ties in the communication network could help make improvements in the project network going forward. SNA offers a chance to generate quantitative data, allowing learnings that are typically not available to project organizations.

On a local level in a project network, SNA can help identify where new ideas and innovative content originate within a network as well as which actors are receivers of these ideas. Such information on innovation diffusion in a network can be a valuable resource when building new project teams or making adjustments to improve a project team's performance. In other words, it is a way to recognize contributions to a project that occur outside of formalized team structures and information exchange protocols.

6.2.2 Accessibility and Trust-building

The specific power of SNA in the context of project organizations is that it is a method to get quantitative data as well as visualize it. It offers the chance to make data accessible to all stakeholders within the network in an intuitively understandable format and to communicate findings outside of the project network itself. This can be particularly valuable in an experimental or innovative context. DFAB HOUSE, for example, is the first project of its size and scope realized within the NCCR Digital Fabrication. Little knowledge existed inside the organization about the challenges of planning and executing a multi-technology demonstrator of its scale. Due to the novelty of the project itself, there was also little precedent to study in advance.

The results of the network analysis provide a framework for management to understand every project participant's contribution, and for project participants themselves to rationalize their stake in the project's success. When asked, key participants found that the data produced by this research supports their own ideas of the network structure and helped verify their "gut" assessment of its benefits. This shared perspective can help build trust in a type of project organization that is characterized less by formal affiliations and specialization than by informal, cross-disciplinary ties and unpredictability.

6.3 LIMITATIONS

DFAB HOUSE is a single case study. The results therefore reflect the individual constraints and contextual factors of this specific case. Generating additional data through further case studies will allow a more comprehensive understanding.

51 out of 147 identified stakeholders responded to the survey. 37 respondents completed the survey. 14 respondents partially completed the survey. The relatively low response rate may impact the accuracy of the results. The results were also limited by the scale of the study. Respondents were asked to provide no more than 30 names of people with whom they interacted although they may have interacted with a larger number of stakeholders. Therefore, the network data obtained through the survey is limited.

The data available stems from a one-time survey during the execution phase of the project. Data from earlier project phases is not available as the survey focused on the project phase in progress at the time when it was conducted. This places the emphasis on horizontal integration in the network rather than on a vertical or longitudinal perspective for which further studies will be necessary. To take these additional perspectives would be useful to study the evolution of the network over the duration of a project and beyond. Nevertheless, as a first attempt to use social network analysis in studying digital fabrication processes, the study reveals some interesting findings that are worth further investigation in future research.

6.4 IMPLICATIONS AND FUTURE RESEARCH POTENTIAL

The significance of interdisciplinarity for systemic innovation requires increasing knowledge exchange across discipline boundaries (Taylor and Levitt 2004, Sheffer 2011, Hall et al. 2014). To achieve this level of interaction will require systemic changes in construction process organization. Little research has looked at specific interaction between individuals and forms of collective solution finding when attempting to implement digital fabrication technologies. SNA can generate quantitative data to better understand and communicate these processes. This data could help, for example, to establish links between bidirectional information flows and collaborative, solution-oriented workflows and their impact on project performance and innovation diffusion.

Ongoing research will complement the results of this study with qualitative information gained through stakeholder interviews to allow further insights into the benefits and challenges in interdisciplinary settings. Extending the quantitative analysis to several case studies could help substantiate our preliminary findings. Studying other comparable demonstrator projects in particular could help understand the potential of construction demonstrators to enable innovation diffusion in the AEC sector.

In future case studies, repeating the survey in several project phases will allow us to take a vertical integration perspective. Multiple comparable case studies could become the basis for a longitudinal study.

7. CONCLUSION

This study, a single case study of DFAB HOUSE, an innovative construction project featuring digital fabrication technology in construction, shows an exemplary organizational structure for the implementation of digital fabrication in construction. Due to the fragmented structure of the AEC sector today, the adoption of digital fabrication is expected to be slow moving and difficult, regardless of the potential benefits of digital fabrication technology to improve productivity, quality and sustainability in the construction industry. Our findings show how the implementation of digital fabrication, a systemic innovation, benefits from an integrated and collaborative model of project organization. We used social network analysis as a method to collect and visualize data on these processes. We showed this to be an effective way to assess the organizational structures at work when implementing novel digital fabrication technologies in an innovative construction project. Our findings allowed us to draw conclusions regarding types of integrated, interdisciplinary project structures that could prove effective for the future adoption of new technologies in the AEC sector.

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