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TITLE: Sustaining and Transcending Boundaries: Innovation Notions, Narratives, and Networks in Digital Fabrication Year 2015-2024

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Introduction

Transcending disciplinary boundaries in technological innovation for construction is imperative to ensuring a resilient future of construction. While many technology designers for sustainable construction would agree with this statement, the potential of cross-disciplinary research collaborations for a digital transformation in construction has not been fully explored and exploited. We base this argument on insights from a literature review of 184 publications from a large research centre dedicated to the institutionalizing of digital fabrication (D-FAB) – an emerging research field in construction.

The presented study is part of a research project that investigates and evaluates major innovation trends in research for sustainable construction. Adopting the notion of 'institutional entrepreneurship' (Zilber, 2007), we highlight the authors' innovation focus and concept and argue that publications on digital fabrication only rarely emphasize innovation beyond 'technological solution'. Largely overlooking the potential impact their technology

might have for ‘good work’ (i.e., job satisfaction, safety, craft knowledge) in construction, and – to an extent – for ‘good construction’ (i.e., efficiency of time, cost, and material), we find that innovation narratives in D-FAB could benefit from adding socio-economic perspectives.

Theoretical background and research questions

As the biggest contributor to CO2 emissions of all industries, the architecture, engineering, and construction (AEC) sector is trying to innovate its ways of building. One of the great promises of innovation in the last two decades has arguably been the emerging research field of D-FAB, digitalizing conventional processes (Oesterreich and Teuteberg, 2016). D-FAB (such as robotic fabrication and 3D printing) differs fundamentally from conventional means of construction as it combines design and construction into an integrated process through programming languages, giving promises of customized building components at lower cost whilst improving efficiency, reducing waste, and increasing on-site safety (Graser, 2020). However, the application of digital fabrication in construction is still in its early stages, and technology designers are constantly looking for industry partnerships to create use cases for their designs. Studies have argued that systemic innovations (such as D-FAB) are three times less likely to be adopted by the industry than modular or incremental innovations (Sheffer 2011, Katila et al 2018). So, at this point in time, how should D-FAB be conceptualized as an innovation force in the AEC sector?

Conducting a research investigation and evaluation of D-FAB as an innovative force in construction over the past decade, we are interested in determining and analysing the main innovations and innovation narratives in the digital fabrication research community: When

does one decide that new technology is innovative? Is it novelty alone, or is it about societal impact?

We ask these questions at the intersection of Zilber's institutional entrepreneurship (Zilber, 2007) and an author network analysis, and in the context of technological innovation for the AEC sector. On the one side, the research is motivated by describing the status of digital fabrication as an innovation power in AEC by identifying key actors, technologies, and collaborations, and on the other side by understanding the innovation narratives that key actors bring into play to institutionalize D-FAB. By reflecting conceptually on the notion of innovation that is propended in the author network we analyze, we may draw the contours of epistemic assumptions in the research culture of digital fabrication (Knorr Cetina, 1999).

The paradigmatic case: Publications from a D-FAB research centre

The research examines 184 publications (Figure 1) published open-source as part of research conducted at a large research center in Switzerland called "the National Centres of Competence in Research – Digital Fabrication" (NCCR). An NCCR is a 12-year research center funded by the Swiss National Science Foundation with the aim of institutionalizing emerging research fields at the intersection of diverse disciplines and industry/society.

We propose that NCCR DFAB presents a paradigmatic case (Flyvbjerg, 2006, 232) for our interest group (digital fabrication researchers), and thus that the trends we describe based on the literature review hold relevance beyond the NCCR DFAB community. The paradigmatic case is a form of case study described by case study researcher Bent Flyvbjerg (2006). While qualitative in their scope, paradigmatic cases are rigorous because they are chosen with

careful attention to their relevance and representativeness (ibid). A powerhouse in digital fabrication research over the last decade, we assume that the NCCR DFAB offers a relevant paradigmatic case for our research. By identifying innovation narratives of this globally significant research community, we might estimate the status of digital fabrication as an innovative force in the AEC sector more widely.

Methodology

Our literature review of innovation in NCCR D-FAB is based on a word frequency analysis. The review took several steps: First, we traced the first mention of digital fabrication in construction literature to Kolarevic (2001) and gained an overview of the technologies associated with the term digital fabrication using the software VOSviewer. Second, we selected articles published from 2015 to 2024 (September) as listed on the NCCR D-FAB publications website. Having selected the papers, as a third step, we determined the technology that was claimed to be innovative by the authors. We did this by scanning the abstracts[1] of the filtered publications for words connoting innovation, summarized in a heatmap of the top 40 most frequent keywords sorted by occurrence, finding that 3D printing with concrete has been the main innovation (figure 2)[2]. In this step, all review papers and commentary papers were also excluded from the data pool.

Fourth, we conducted a content analysis whereby we could "assign a unit of text to more than one category simultaneously (Tesch, 1990)." We chose the content analysis method because

[1] The decision to narrow the review of the publications to their abstracts reflects pragmatic reasoning: We rationalized that the authors would likely highlight the most important innovation in their research in the abstract. Since we were interested in the authors' perspective, this would make for a good filter besides saving us time.

[2] 3D printing with concrete is argued to be the main innovation based on the heatmap analysis for keywords by occurrence from the interpretation of the results that the 3 of the 6 most occurring keywords are "concrete", "3D" and "print". In addition, "fabrication", "design" and "formwork" – the remaining words in top 6 – are more generally applicable keywords that could also occur in a paper about 3D printing with concrete. In other words, this is the technology that appears in most papers.

of its potential to systematically identify, analyze, and interpret meanings in a more structured manner than other approaches, such as thematic analysis. We selected innovation keywords in the papers inspired by Breuer and Mueller (2024), who have identified that technology is promoted with the narratives of "technological assistance," the provision of "good care," and the facilitation of "good work" within the healthcare sector. Drawing from this structure, we selected three categories in which the notion of innovating technology is defined within the NCCR DFAB community, including "technological solutions", "good construction" and "good work'. Then, following a "recipe thinking" by Wu et al. (2024) that argues that technology design is a result of configuring multiple conditions simultaneously, as a fifth step, we divided the categories into sub-groups of keywords, used to construct the innovation narratives: First, 'technological solutions' which comprises the subgroups 'new workflow', 'new form', 'new material' and 'data'; second, 'good construction' which comprises the subgroups 'time efficiency', 'cost efficiency', 'material efficiency', 'sustainability', 'simplification of processes' and 'technology transfer' and third 'good work' which comprises the subgroups 'safety', 'ergonomics', 'interesting work', 'enhanced skills' and 'back to craft'. For every recipe categorization, a quote from the abstract supporting the categorization choice was extracted. If there were several categories for one publication, we placed them in the same field and indicated the corresponding quote using numbering. If no direct link to a category was found, we categorized N/A (Figure 3).

As a sixth step, we created a network of authors and co-authors from all the publications by gathering the author information in Endnote Reference Management Software and subsequently analyzing the EndNote library file (.enl) in VOSviewer using "association strength" as a normalization method. Names of authors were removed for anonymization

purposes. The network revealed authors with a high number of publications, with five authors as 'main authors'.[3]

Results[4]

Figure 3 visualizes the number of published papers describing a D-FAB innovation. The distribution reflects the authors' representation of their research as innovative, presenting the contours of a discourse of innovation in NCCR D-FAB. There are very few publications that address 'good work', and relatively few addressing 'good construction'. Under 'good construction' only technology transfer is regularly mentioned, with attention given to sustainability and efficiency in time, money, and material (often linked to sustainability in D-FAB innovation narratives). The highest number falls under 'technological solution', with new workflows and computational advancement being the main contributions. This is perhaps not so surprising given that most publications will be additions and transformations of existing technologies (i.e., a new workflow for 3D printing with concrete) rather than an entirely new technology. Still, it is plausible to argue that the focus has been on technological innovation.

This finding motivates further reflection and questioning: Why is "good work" not better represented? Which factors drive innovation in D-FAB? Who is behind the numbers? To further investigate such questions, we started analyzing the author network behind the publications (Figure 4). From a perspective of institutional entrepreneurship (Zilber, 2007),

[3] Preparing the author network analysis, we controlled for whether the high publication numbers could be explained by authors' self-referencing. Doing this, we looked at the strength of the connection between the reference points (the five selected core authors of the NCCR D-FAB innovation network) and peripheral authors (identified through citations). We found that there was a significant amount of self-referencing but not to the extent of undermining the analysis of the main authors and their innovation technologies.

[4] Coding files, further versions of figures, etc., are stored in a Google Drive file shared among the authors of this paper. These files can be accessed upon request.

the authors in the D-FAB network are seen as strategic actors whose success depends on how well they can align their innovations with institutional demands. As a result, they focus their innovation narratives on specific aspects (Figure 3) and engage in specific networks (Figure 4). The author network is based on all authors of all D-FAB publications and is contrasted by a citation network (included in Figure 5 with the author network) which is based on the bibliography of 5 selected authors' three most cited publications (i.e., a network of the authors that have been cited in these three publications). The network shows a core of relatively few, highly interconnected researchers, and an array of researchers who are more peripheral to the discourse and typically connected to the core via a single researcher – a gatekeeper. The five authors selected as reference points for the author network analysis are, in combination, involved in a very high number of D-FAB publications, with the network integrating around these core authors who set the discourse. We have anonymized the authors in the figures available here, but we have based our analysis on a non-anonymized version to reflect the network against the background of the authors' academic profile. They represent disciplinary profiles across architecture, structural design, material science, and civil and chemical engineering. Some collaborations with more peripheral D-FAB innovation profiles, such as construction management and economics, and work and organizational psychology, can be identified alongside frequent collaborations with computer scientists.

Despite a truly multi-disciplinary network, a highly networked core of researchers focusing on 'technological solution' has set the tone for the D-FAB innovation discourse over the past decade. While these core researchers represent diverse disciplines and, to an extent, transcend disciplinary boundaries with their research, this tendency leaves the potential to highlight other innovation narratives in future research. For example, the impact on construction work is only minimally represented, leaving space for foresight analysis of the automation impact of the technologies presented in the papers.

Conclusion

Based on a literature review (N=184) of publications from a research centre dedicated to the emerging field of D-FAB and its institutionalization, we have identified major innovation concepts, narratives, and networks and pointed to future potentials.

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Figures

Figure 1: Included research papers

Included papers published until 03 September 2024 at
https://dfab.ch/publications/_category/conferencepaper#:
Number of papers published: 204
Years: 2015-2024

Number of papers included in analysis: 184

year	total	included	no fulltext	review/commentary
2015	4	3	1	0
2016	17	17	0	0
2017	22	21	0	1
2018	36	33	1	2
2019	38	32	2	4
2020	29	27	1	1
2021	22	20	1	1
2022	17	16	1	0
2023	15	11	0	4
2024	4	4	0	0
total	**204**	**184**	**7**	**13**

No of papers excluded: 20
Full text not available: 7
Review or commentary: 13

Reduction steps:

Included papers published until 03 September 2024 at
https://dfab.ch/publications/_category/conferencepaper#.

1. Fetched pdf versions of each publication from ETH Research Collection (https://www.research-collection.ethz.ch/) or, if not found there, through search of other online repositories. Papers where no full text version was available were excluded.
2. (Semantic analysis of full text for word frequencies. Included all papers here, also reviews and commentaries).
3. Analysis of abstracts according to the recipe categories. Review and commentary papers were excluded in analysis.

Figure 2: Heatmap of the top 40 most frequent keywords sorted by occurrence

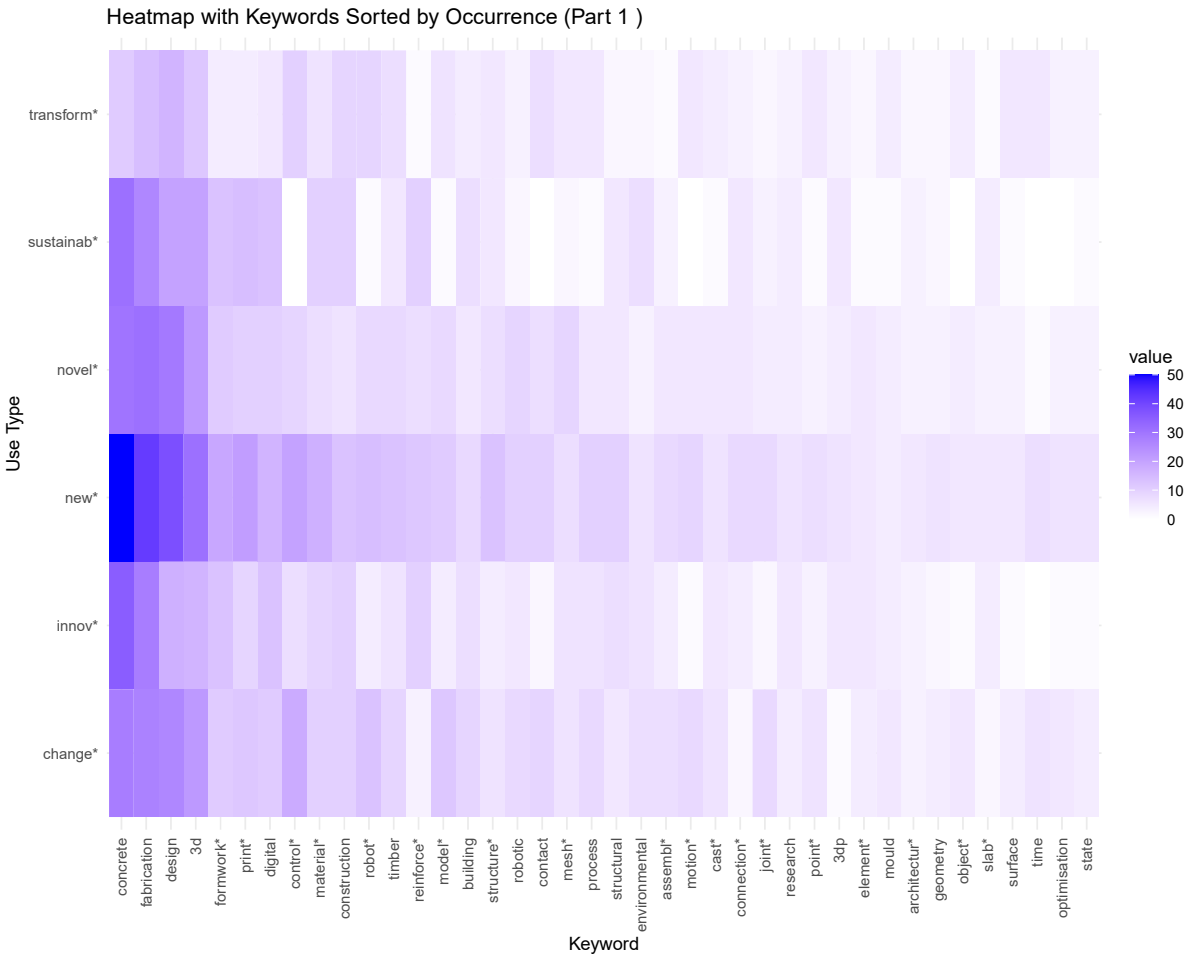


Figure 3: Distribution of papers into innovation categories

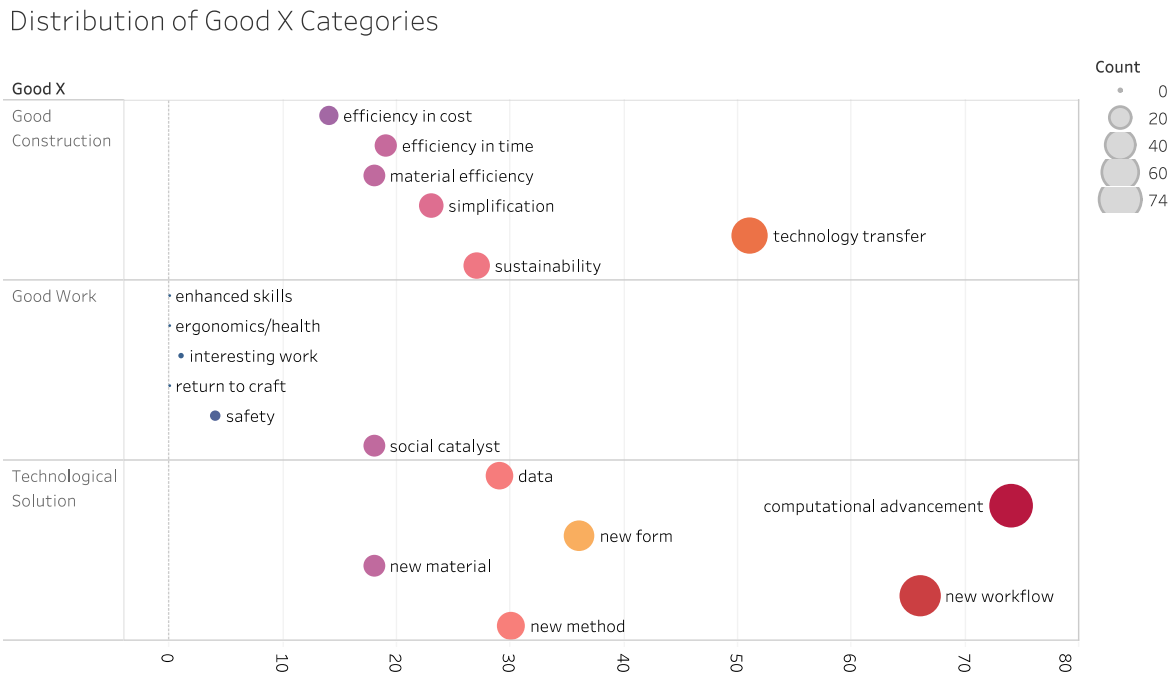


Figure 4: Author network (anonymized version)

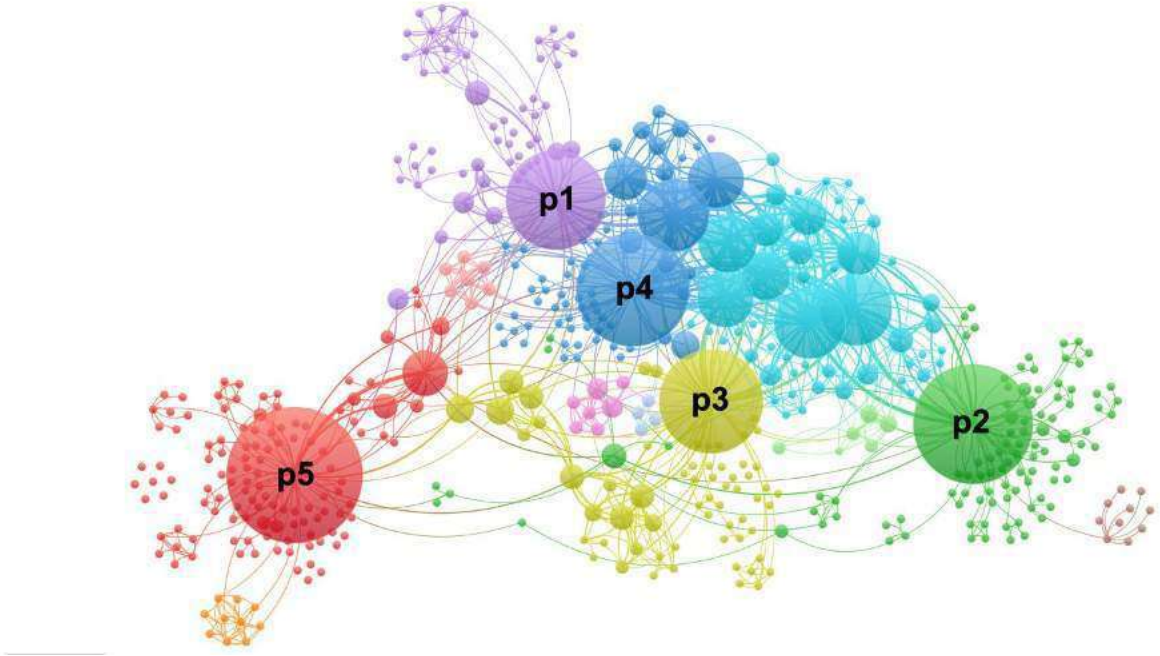
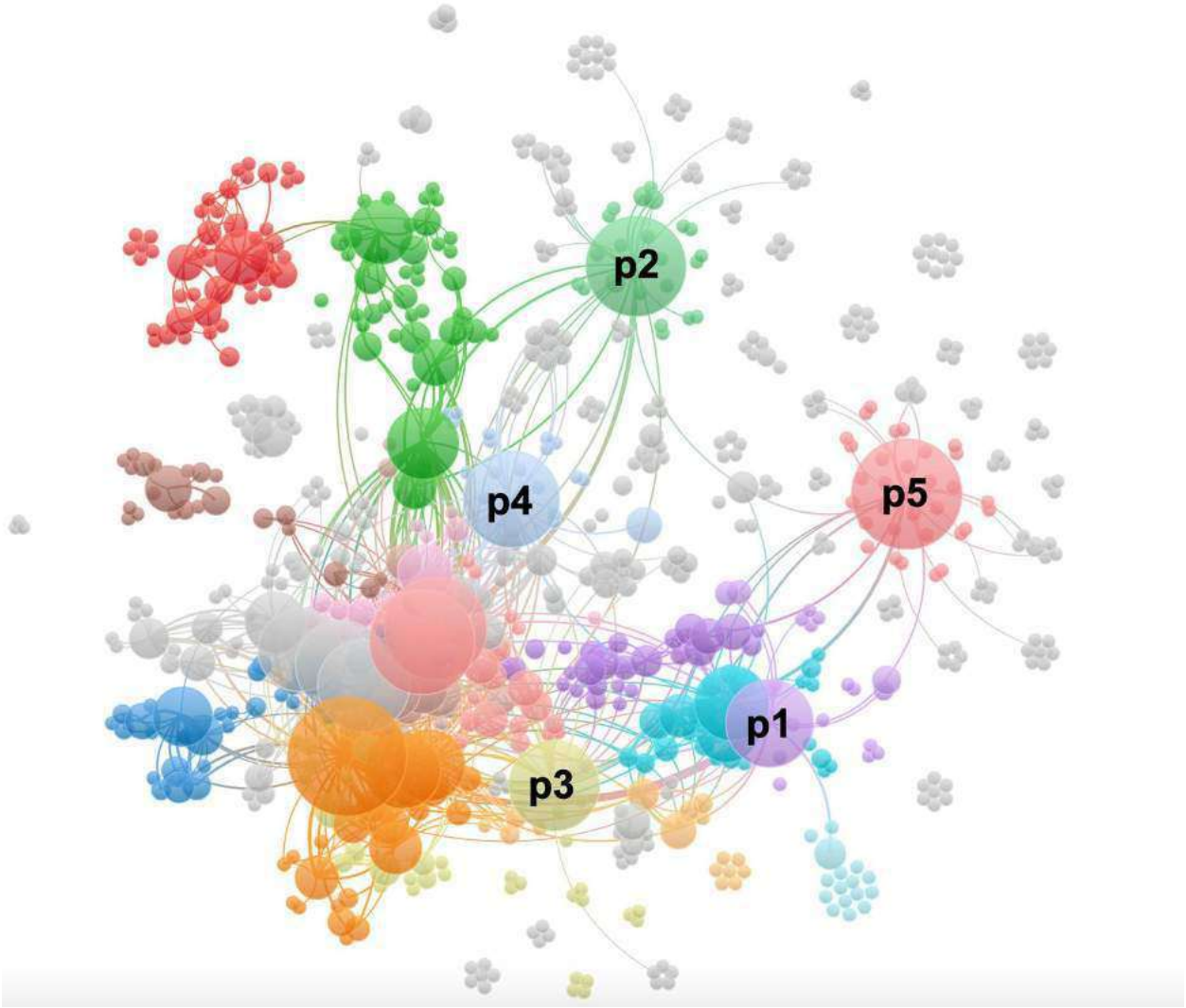


Figure 5: Author network and citation network (anonymized version)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