Design for Digital Fabrication: an Industry needs Analysis of Collaboration Platforms and Integrated Management Processes

Ming Shan Ng[a], Marcella M. Bonanomi[a b], Daniel M. Hall[a] and Jürgen Hackl[c]

[a]Chair of Innovative and Industrial Construction, ETH Zürich, Switzerland
[b]Polis-Lombardia, Italy
[c]School of Engineering, University of Liverpool, U.K.

ng@ibi.baug.ethz.ch, bonanomi@ibi.baug.ethz.ch, hall@ibi.baug.ethz.ch, hackl@liverpool.ac.uk

Abstract -

Digital Fabrication is an emerging systemic innovation in the architecture, engineering and construction sector. However, the design process for digital fabrication lacks an integrated management process or digital collaboration platform. One reason may be a lack of industry stakeholder needs for such processes and platforms. To explore and facilitate such solution in the current practice, more information about the socio-technical industry requirements on such solution and its implementation to support and manage the BIM-based design process of digital fabrication is needed. To fill this gap, this work conducts an industry-needs analysis through content analysis and an online survey of 144 project stakeholders. Based on the results, this work identifies the most needed fabrication-related information, tools and roles at different design stages and the requirements of platform-based management, which include a common virtual environment for collaboration and a common data environment for data management. Moreover, this work shows that fabrication-related information and new roles are required by project stakeholders since the early design stage. The paper concludes by proposing a conceptual management framework for BIM-platform-based integration for design for digital fabrication in construction projects and identifying potential future research directions on the topic.

Keywords -

BIM, platforms, digital fabrication, design process, project management, survey

1 Introduction

Digital fabrication is an emerging systemic innovation in the architecture, engineering and construction (AEC) sector. In this work, digital fabrication refers to the aspects of industrialised construction, off-site fabrication and /or modular construction that connect design and construction with a digital thread using an integrated process that controls machinery during fabrication tasks [1]. Despite many research and demonstration projects [2], the industry is slow in adopting and implementing digital fabrication due to identified barriers such as skeptical attitude towards DFAB from project stakeholders and complexity in managing process and deliverables [3]. Furthermore, digital fabrication changes the requirements of the design process and requires a new framework in which to guide collaboration between designers and fabricators [4].

To facilitate the design process of digital fabrication, scholarship to date has proposed adoption of new management models such as lean design management and new design approaches such as design for manufacture and assembly (DfMA). These efforts have attempted to bring downstream fabrication information into the upstream design process. The objective of these methods is to facilitate process integration in design and construction [5]. However, an integrated management process specific to digital fabrication does not yet exist.

In addition, there are few digital collaboration platforms available to facilitate an integrated design process for digital fabrication. Digital collaboration platforms are cloud-based platforms for multidisciplinary stakeholders to co-create design deliverables in the design process for tendering and construction. Digital fabrication requires a restructured collaboration process that can support new stakeholders' early involvement and break the wall between design and construction for collective knowledge exchange [2]. Digital fabrication should also connect to ongoing AEC digitalisation approaches such as Building Information Modelling (BIM). Both digital fabrication and BIM aim to help to improve various aspects of integration and foster systemic innovation in the current practice [6]. However, both approaches require a change in management of project life-cycle from planning to construction [2, 7]. Furthermore, the adoption of digitalisation is slow compared to many other industries in the current practice [8, 9]. Nevertheless, a BIM-based collaborative design platform that can support collaborative design for digital fabrication in construction does not yet exist [5]. One potential reason for this is that industry requirements for such platforms are not yet identified.

To fill this gap, this work aims to investigate and analyse the industry requirements for BIM-based collaboration platforms and platform-based integrated management for design for digital fabrication. Based on the industry needs analysis, this work presents a conceptual framework that manages BIM-based collaborative design process of digital fabrication in projects. To do so, the authors first conduct content analysis of literature review to identify and categorise the requirements of such platforms. The identified requirements are composed in a questionnaire for an online survey of industry experts who have experience in the design and/or construction processes of digital fabrication. Based on the survey results, the authors analyse the industry requirements for such platforms and platform-based management for the design process of digital fabrication. The authors then develop a conceptual management framework for platform-based integration in response to the survey results and the industry needs analysis to address the industry requirements.

This work is organised as follows. Section 2 provides a brief overview of digital fabrication and BIM-based collaboration platforms. Section 3 contains a description of the research design and the survey. Section 4 presents the findings of the conducted survey and the industry needs analysis. Subsequently, Section 5 proposes a conceptual framework for platform-based integration and identifies future research. Section 6 concludes with remarks and suggestions for further work.

2 Background

The architecture, engineering and construction (AEC) sector has been fragmented vertically in processes from design to construction, horizontally among project teams, and longitudinally across projects [6]. In particular, the design process is the root cause of many project life-cycle problems, such as quality and cost misalignments and low productivity in construction [10]. Scholars suggest the construction industry has been caught itself in a "mirror trap", where knowledge is trapped tightly with the task dependencies themselves [11]. Thus, the industry resists attempts to innovate. In order to overcome this resistance "disruptive paradigms" are in need [12]. The use of new approaches such as digital fabrication provides the opportunity for integration and systemic innovation that can be key for such a change [13].

In order to bring digital fabrication from theory into practice, scholars suggest digital system-based management approaches can provide better integration [1, 6]. Hall et al. [13] identified digital systems integration as a firm-based "mirror-breaking" approach to adopt digital fabrication. This involves web-based configuration platforms for flexible kits-of-parts to integrate supply chain for design to enable digital production. García de Soto et al. [14] also propose the use of cloud-based platforms and platform-based integration as a project-based approach to implement digital fabrication from design to construction. Such platform-based management requires new roles and new tasks in both design and construction processes. Platform-based integration supports operational and management-related technical requirements for BIM-based collaboration platform. It facilitates the adoption of technologies and intelligent and automated collaboration in design and construction, supply-chain management and systems integration [15]. This includes BIM-based collaboration platforms that allow stakeholders to engage, co-create, communicate, coordinate and collaborate design in a common virtual environment for design modelling in 2D and 3D, design review and project management. Such platform facilitates information exchange and knowledge sharing for design review, progress monitoring and optimisation of cost and constructability, as well as immersive environments for collaboration and the adoption of automation and innovation in design process [7, 16]. BIM-based platforms provide measurable data for progress tracking, risk management, trust-building and benchmark of deliverables for quality control and trade tendering, and supports design integration and integrated management [4, 17].

3 Research Design

To investigate and analyse the industry requirements for BIM-based collaboration platforms and platform-based integrated management for design for digital fabrication, the authors conduct (i) content analysis of literature review, (ii) an online survey with a multiple-choice questionnaire, and (iii) analyses and visualisations of the results.

Firstly, this work involves a content analysis of literature review to identify, condense and categorise the requirements for collaboration platforms in the design process of digital fabrication in construction projects [18]. The authors conduct two rounds of keywords search to screen and review literature published in the past ten years. In the first round of literature search, the keywords used are "digital fabrication", "design process", "collaboration" and "parametric". In another round, the keywords used for literature search are "collaboration", "design process", "platform" and "BIM". Amongst all, the authors filter irrelevant contents to identify the operational and management requirements [15]. The authors group the requirements into five categories, namely technical, technological, organisational, contractual and business-related requirements.

Secondly, based on the content analysis, the authors compose 18 questions in a multiple-choice questionnaire to undertake an anonymous online survey of the industry stakeholders with digital fabrication design and/or construction experience. Each question is composed of seven to twelve multiple choice answers. For most of the questions, participants could choose a minimum one and maximum of three choices. The goal of this survey is to understand the industry needs for collaboration and integration

country	Switzerland	United Kingdom	Italy	U.S.A.	Japan	Singapore
Terms in this survey	**SIA Leistungsmodell**	**RIBA Plan of work 2020**	**ITA Procurement**	**AIA Phases of Design**	**TAAF 設計から完成までの流れ**	**BCA Stages**
Strategic Definition	1. Strategische Planung	0. Strategic Definition	progetto di fattibilità tecnico-economica	Project Brief	企画 (kikaku)	Project Brief
Feasibility Study	2. Vorstudien	1. Preparation & Brief		Pre-design/ Concept	基本設計 (kihonsekkei)	Concept Design
Schematic Design	3.1 Vorprojekt	2. Concept Design	progetto preliminare	Schematic Design		
Detailed Design	3.2 Bauprojekt	3. Spatial Coordination	progetto definitivo	Design Development	実施設計 (jisshisekkei)	Detailed Design
Technical Design	4. Ausschreibung	4. Technical Design	progetto esecutivo			Pre-Construction
Documentation				Construction Documentation		
Construction	5. Ausfürhung	5. Manufacturing & Construction	costruzione	Construction	工事監理 (koujikanri)	Construction
Handover	5.3 Inbetriebnahme	6. Handover	collaudo e consegna	Commission	完了検査 (kanryokensa)	Post-Completion
Operation	6. Bewirtschaftung	7. Use	uso e manutenzione	Occupancy	建物使用 (tatemonoshiyō)	

Table 1. Design stages terminology in this work in reference to the plans of work in Switzerland, U.K., Italy, U.S.A., Japan and Singapore

platform for the design process of digital fabrication in construction.

To assist stakeholders in their survey participation, the authors summarise a comparison of the design stage terminology in existing plans of work in six countries as shown in Table 1. To promote comparative international responses, the definitions are summarised in accordance with the plans of work from Swiss Society of Engineers and Architects (SIA) in Switzerland, the Royal Institute of British Architects (RIBA) in the U.K., Italian (ITA) Procurement Law in Italy, the American Institute of Architects (AIA) in the U.S.A., Tokyo Association of Architectural Firms (TAAF) in Japan and the Building and Construction Authority (BCA) in Singapore, as well as the authors' first-hand work experience in projects in these six countries. The definitions of the design stage terminology might vary project by project, company by company. Thus, Table 1 merely serves as a reference to the terminology for the survey participants.

Thirdly, this work visualises and analyses the results of the industry needs analysis based on the survey [15]. Fourthly, based on the survey results, the authors propose a conceptual management framework for platform-based integration to manage BIM-based design process of digital fabrication in construction projects, and propose future research areas.

4 Findings

Based on the content analysis, the authors elaborated 18 questions in five categories. (1) *Technical requirements* are digital fabrication specific. During the design process, fabrication information and machine code are often required from downstream to upstream decision-making [2]. Moreover, tools such as sensors are used to keep track on the motions of the fabrication machines to ensure consistency between the digital design model and the digital fabrication performance [4]. (2) *Technological requirements* are platforms specific. The authors identify the current trends in cloud-based collaboration platforms for BIM-based design process. Such platform supports multidisciplinary information exchange and constant feedback

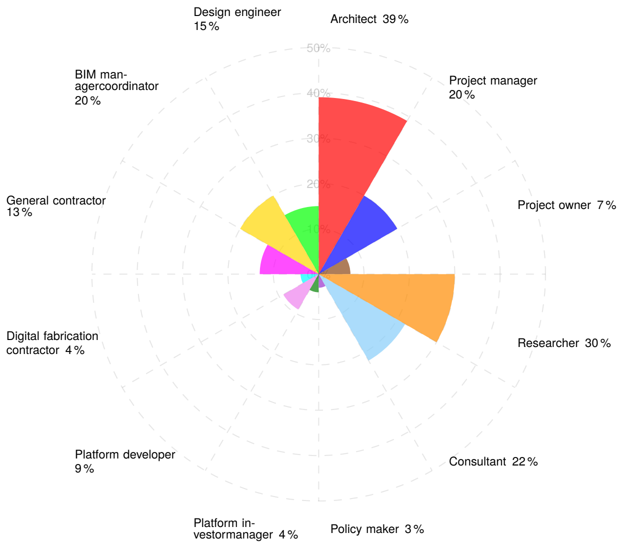

Figure 1. Summary of professions of the online survey participants

loops between design and fabrication, and facilitates cocreation and BIM data management for project integration [14, 15, 17]. (3) *Organisational requirements* are digital fabrication design project specific. Implementation of digital fabrication restructures a project's organisation and supply-chain [6, 13]. New roles such as digital fabrication (DFAB) manager and DFAB design coordinator, are evolved in projects. This is similar to the new roles derived due to BIM implementation in projects [7]. While several existing downstream roles such as DFAB programmer are required to participate in the upstream decision-making [14, 19]. (4) *Contractual* and (5) *business-related requirements* are platforms specific. Platform-based integrated management derives new contractual and business strategies to ensure such novel design management approach for process integration, organisational integration and information integration [5, 13, 17]. These two categories are not analysed and presented in this work.

In May 2020, the authors undertook an anonymous online survey of the industry experts who have experience

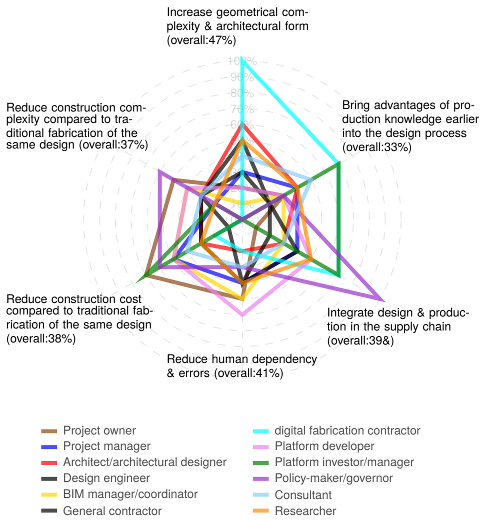

Figure 2. Primary motivations from project stakeholders

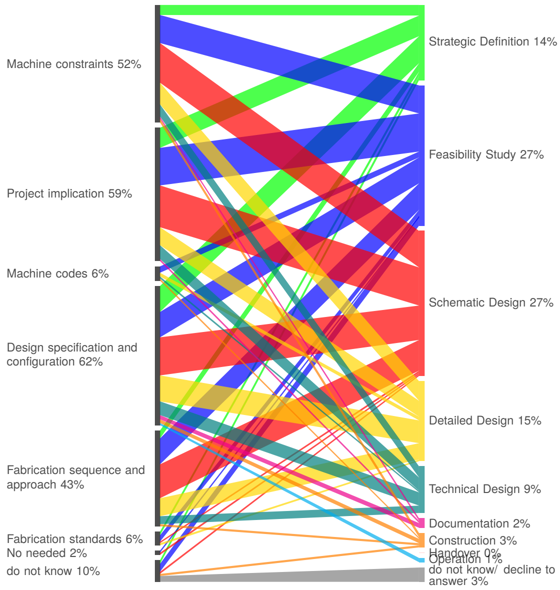

Figure 3. Most needed fabrication-related information at each design stage

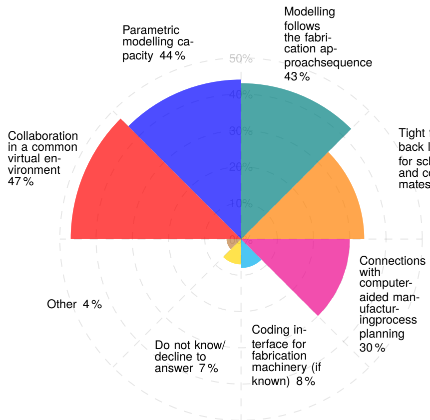

Figure 4. Most needed aspects in design modelling for digital fabrication

in digital fabrication in design and/or construction. The survey received 144 responses. Figure 1 shows a summary of the professions of the survey participants. Amongst all, one-third of the participants and one-forth have more than five years of digital fabrication experience in design and in construction respectively.

The following paragraphs describe the fabrication specific *technical requirements* in BIM-based design process of digital fabrication. Figure 2 illustrates in a spider-web diagram the primary motivations of the project stakeholders for design for digital fabrication over traditional construction processes. The overall percentages of each answer are listed. It also shows that the primary motivations of different professions are not the same. The answers exclude the option of construction quality, which is commonly seen as the most popular motivation [1, 2, 3, 5, 14].

Figure 3 differentiates and illustrates in a bipartite-sankey diagram the most needed fabrication-related information at each design stage in the design process of digital fabrication as per the terminology defined in Table 1 is the fabrication-related information first needed. The overall percentages of each most needed information and the overall percentages of each design stage are listed. Figure 3 reveals that various different types of fabrication-related information are in fact needed since the early design stages.

Figures 4, 5 and 6 illustrate the most needed aspects in design modelling, design reviews and design documentation respectively in the design process of digital fabrication in construction projects. Regarding design modelling, Figure 4 shows that the answers are quite evenly distributed among all the multiple choices answers. 4% of the participants provided other answers such as fabrication machines and process constraints are also needed for design modelling to meet fabrication tolerances; interactions between design modelling and fabrication tools such as robotic arms and collaborative mindsets among multidisciplinary stakeholders are also needed in terms of fabrication-related information in design modelling. Regarding design review, the survey results as illustrated in Figure 5 reveal that over half of all the participants expressed their needs in process visualisation and simulation and collaboration in a common virtual environment. 4% of the participants provided other answers such as options such as optimisation, design status scheduling and tracking and information to connect to the factory floor are also needed for design review. Regarding design documentation, Figure 6 shows that the stakeholders needs are also quite evenly distributed amongst all answers. 2% of the participants provided other answers such as configuration

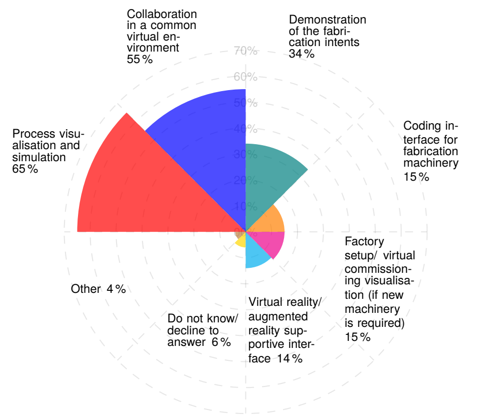

Figure 5. Most needed aspects in design review for digital fabrication

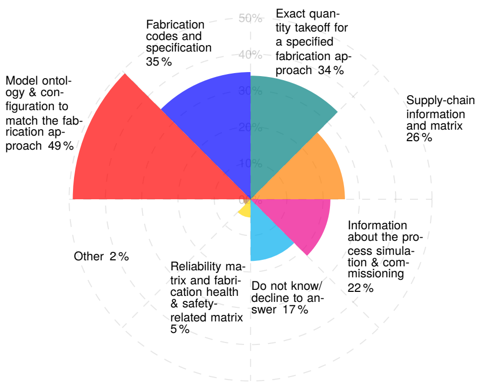

Figure 6. Most needed aspects in design documentation for digital fabrication

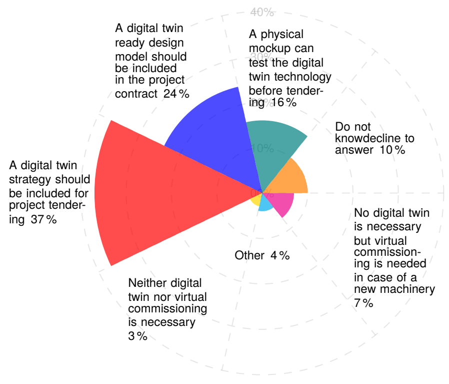

Figure 7. Most needed digital twin strategy for design for digital fabrication

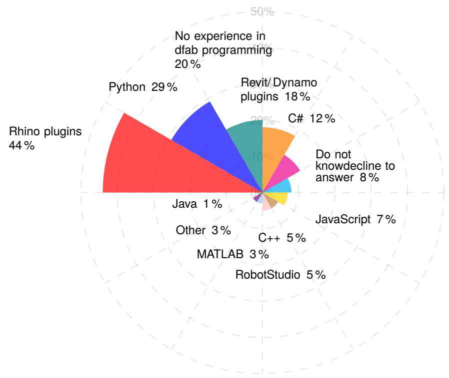

Figure 8. Most used platforms and programming languages for design for digital fabrication in the current practice

management is also needed for design documentation.

Figure 7 illustrates the most needed digital twin strategies for design for digital fabrication. Only 3% of the participants required neither digital twin nor virtual commissioning for design for digital fabrication. 4% of the participants expressed that the digital twin strategies depend on the complexity and delivery models of the projects.

The following paragraphs describe the platforms specific *technological requirements* in BIM-based design process of digital fabrication. Figure 8 illustrates the background information of the platforms and programming languages being used in the current practice. 3% of the participants provided other answers such as solidworks, cadwork and Robot Operating System.

Figure 9 differentiates and illustrates in a bipartite-sankey diagram the most needed ways to support machine code on the collaboration platforms for project stakeholders to edit at each design stage in the design process of digital fabrication as per Table 1. The overall percentages of each most needed ways of support and the overall percentages of each design stage where such support is first needed are listed. 5% of the participants provided other

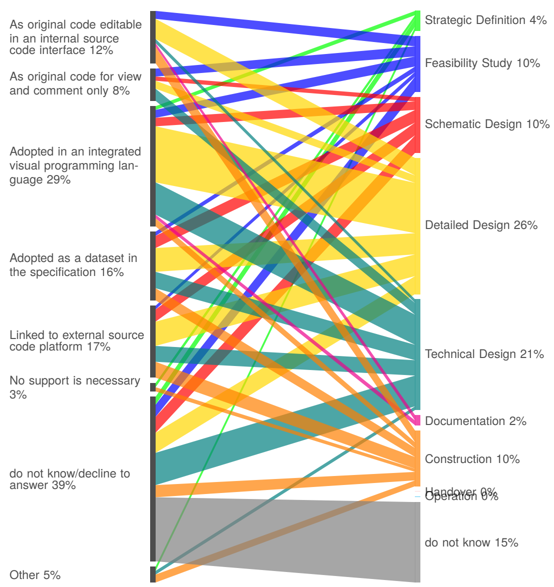

Figure 9. Most needed ways to support machine-code on cloud-based platforms at each design stage

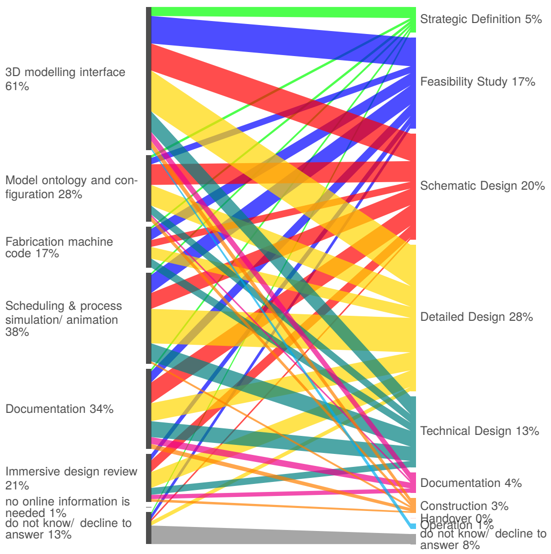

Figure 10. Most needed fabrication information shared on cloud-based platforms at each design stage

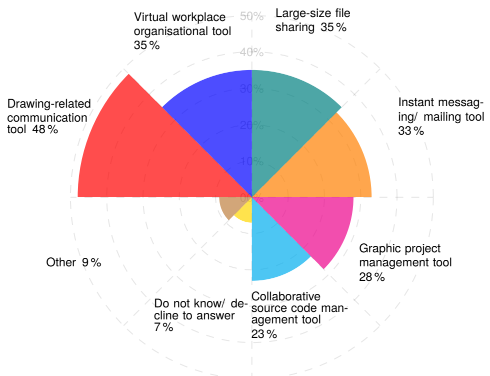

Figure 11. Most needed supporting functions for communication and knowledge sharing on collaboration platforms

answers such as machine code should only be accessible by the fabrication contractor instead of being editable by all project teams on the platforms; another answer is that the ways of support depend on the vary project by project, depending on the project stakeholders' preference. Moreover, only 1% of the participants required no machine-code support on the platforms.

Figure 10 differentiates and illustrates in a bipartite-sankey diagram the most needed digital fabrication information to be shared on cloud-based collaboration platforms at each design stage as per Table 1. The overall percentages of the most needed information to be shared online and the overall percentages of each design stage where such cloud-based sharing is most needed are listed. Only 1% of the participants required no online sharing of digital fabrication. 2% indicated that information sharing on such platforms require a common data environment.

The most needed supporting functions for communication and knowledge sharing on collaboration platforms are illustrated in Figure 11. The answers are quite evenly distributed. The authors especially did not include modelling-related tool because this is by default a must on such platforms. 9% of the participants provided other answers such as issue trackers are needed. They also indicated that the functions require a common data environment for data management.

The following paragraphs describe the digital fabrication design project specific *organisational requirements* in BIM-based design process of digital fabrication. Scholars identified that new roles and new responsibilities are cre-

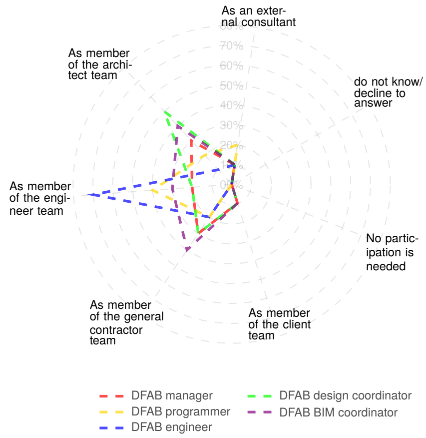

Figure 12. Most needed ways of the new digital fabrication roles' involvements in a multidisciplinary project

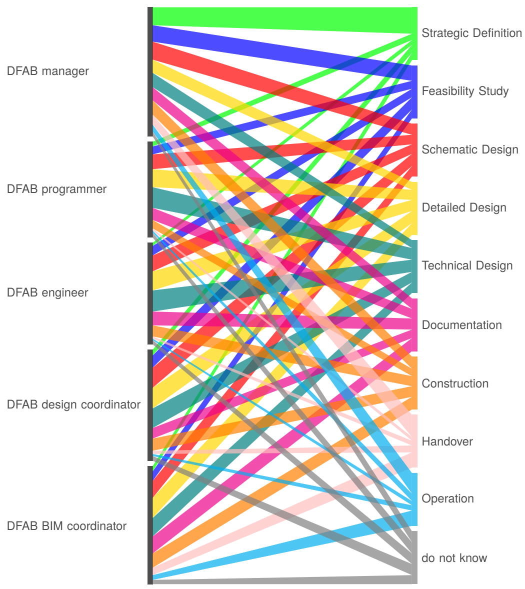

Figure 13. Most needed involvement of the new digital fabrication roles at each design stage in a construction project

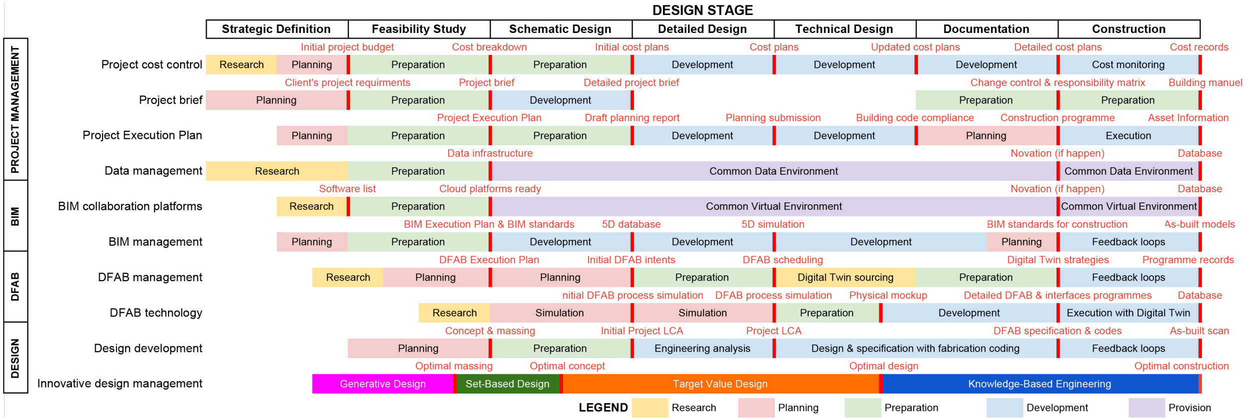

Figure 14. A conceptual management framework for platform-based integration in BIM-based design process of digital fabrication in construction projects

ated in particular for digital fabrication projects [19, 14]. The new roles include digital fabrication (DFAB) manager, digital fabrication (DFAB) programmers, digital fabrication (DFAB) engineers, digital fabrication (DFAB) design coordinator and digital fabrication (DFAB) BIM coordinator. Figure 12 illustrates in a spider-web diagram the most needed ways of the five new roles' involvements in projects. In average only 1% of the survey participants required no new roles in projects. The required ways of involvements are different for each role. All in all, the results show that the new roles should be integrated within the existing project team structure.

Figure 13 illustrates in a bipartite-sankey diagram the answers of the question about when the new roles are needed. The percentages of the roles required in each stage are shown in proportion on the left-hand side. It can be seen that new roles for digital fabrication are not isolated to a single design stage but are needed across multiple phases of design and many of the new roles are required to join the project team since early design stages.

5 Discussion and future research

From the industry needs analysis conducted in this work, implementation of digital fabrication significantly impacts the design process with respect to information exchange, workflow and organisational structure in construction projects. The design process of digital fabrication requires new approaches to design management. The industry has specific requirements for the design process of digital fabrication. These requirements enable platform-based integration and integrated project management for design for digital fabrication to integrate process, information and organisation for construction projects [5, 17]. Moreover, such collaboration platforms should connect a BIM-based design process with digital fabrication through a common data environment. This can enable integrated data management and common virtual environments for project stakeholders to visualise, simulate and coordinate design for digital fabrication.

Based on the survey results, the authors propose a conceptual platform-based management framework to manage a BIM-based design process of digital fabrication (see Figure 14). This framework considers four categories of tasks, namely design, digital fabrication (DFAB), BIM and project management. The framework illustrates how tasks of research, planning, preparation, development and provision at each design stage match with the requirements identified in the survey. The proposed deliverables of the tasks are also indicated in red.

The goal of this framework is to assist project managers and stakeholders to manage the BIM-based design process of digital fabrication in construction projects. Furthermore, in order to facilitate BIM-platform-based integration and integrated project management for design for digital fabrication, the authors propose that emerging design management approaches such as Set-Based Design (SBD) and Target Value Design (TVD) could be considered to manage the design process of digital fabrication.

Future research on how to integrate and manage the complexities of design for digital fabrication could include:

1. An in-depth industry needs analysis to investigate how each aspect of the requirements inter-relate and impact on each other;

2. More detailed statistical analysis of the data such as a paired-means test to determine if answers differ by discipline and /or experience level of the participants;

3. An in-depth research on such platform-based management framework for design for digital fabrication;

4. Further investigation and application of lean design management strategies such as SBD and TVD.

6 Conclusion

One potential reason for the slow adoption of digital fabrication in AEC is the lack of a developed management model to integrate project stakeholders. Existing research identifies that BIM-based collaboration platforms and platform-based integration can help to break through the socio-technical barriers and facilitate the implementation of digital fabrication in the design process in projects. To investigate such platforms and their management approaches, this work conducts an industry needs analysis through an online survey of 144 project stakeholders in current practice. The preliminary analysis finds: (i) fabrication-related information such as specification and project implication is needed since early design stage, (ii) collaboration in a common virtual environment and process simulation are needed in the design process, (iii) model ontology to follow the fabrication approach is required in design documentation, preparation for digital twin in digital fabrication is required before tendering, (iv) digital fabrication information is required to be shared and edit among project stakeholders to different extents at different design stages in a common data environment and (v) new roles such as DFAB manager and DFAB BIM coordinators are required since early design stages and continuing throughout the design process. This work further elaborates a conceptual platform-based management framework to manage such complex BIM-based design process of digital fabrication in construction projects.

References

[1] T. Bock and T. Linner. Robotic Industrialization. *Robotic Industrialization*, 2015.

[2] K. Graser et al. DFAB HOUSE: A Comprehensive Demonstrator of Digital Fabrication in Architecture. In *Fabricate 2020: Making Resilient Architecture*, pages 130–139, 2020.

[3] G. Carra et al. Robotics in the construction industry: State of the art and future opportunities. *ISARC 2018 - 35th ISARC and Intl. AEC/FM Hackathon: The Future of Building Things*, (Isarc), 2018.

[4] T. Svilans et al. New Workflows for Digital Timber. In F. Bianconi and M. Filippucci, editors, *Digital Wood Design: Innovative Techniques of Representation in Architectural Design*, pages 93–134. Springer, 2019.

[5] M.S. Ng and D.M. Hall. Toward Lean Management for Digital Fabrication: a Review of the Shared Practices of Lean, DfMA and dfab. *27th Intl. Group for Lean Construction Conf.*, pages 725–736, 2019.

[6] D.M. Hall et al. Identifying the Role of Supply Chain Integration Practices in the Adoption of Systemic Innovations. *J. of Mgmt. in Eng.*, 34(6), 2018.

[7] M.M. Bonanomi et al. The impact of digital transformation on formal and informal organizational structures of large architecture and engineering firms. *Eng., Construction and Arch. Mgmt.*, ahead-of-p (ahead-of-print), 2019.

[8] F. Barbosa et al. Reinventing Construction: A Route To Higher Productivity. Technical Report February, McKinsey, 2017.

[9] R. Agarwal et al. Imagining construction's digital future. Technical report, 2016.

[10] P.A. Tilley. Lean design management - A new paradigm for managing the design and documentation process to improve quality? *13th Int. Group for Lean Construction Conf.: Proceedings*, (2002): 283–295, 2005.

[11] L.J. Colfer and C.Y. Baldwin. The mirroring hypothesis: Theory, evidence, and exceptions. *Industrial and Corporate Change*, 25(5):709–738, 2016.

[12] R.E. Levitt. CEM Research for the Next 50 Years: Maximizing Economic, Environmental, and Societal Value of the Built Environment. *J. of Const. Eng. and Mgmt.*, 133(9), 2007.

[13] D.M. Hall et al. Mirror-breaking strategies to enable digital manufacturing in Silicon Valley construction firms: a comparative case study. *Const. Mgmt. and Economics*, 0(0):1–18, 2019.

[14] B. García de Soto et al. Implications of Construction 4.0 to the workforce and organizational structures. *Int. J. of Const. Mgmt.*, pages 1–13, 2019.

[15] V. Singh et al. A theoretical framework of a BIM-based multi-disciplinary collaboration platform. *Automation in Construction*, 20(2):134–144, 2011.

[16] M.S. Ng and D.M. Hall. VR/AR in Design Management: Use-cases and Future Research. In *24th Industriebauseminar 2019 Proc.. Vienna, Austria*, pages 55–57, 2019.

[17] M. Fischer et al. A simple framework for integrated project delivery. *22nd Int. Group for Lean Construction Conf.: Understanding and Improving Project Based Production*, pages 1319–1330, 2014.

[18] H.F. Hsieh and S.E. Shannon. Three approaches to qualitative content analysis. *Qualitative Health Research*, 15(9):1277–1288, 2005.

[19] K. Graser et al. Social Network Analysis of DFAB House: a Demonstrator of Digital Fabrication in Construction. In *Eng. Project Organization Conf.*, pages 1–21, Vail, CO, 2019.