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DOI
10.1016/j.iintel.2023.100027

Publication date
2023

Document Version
Final published version

Published in
Journal of Infrastructure Intelligence and Resilience

Journal of Infrastructure Intelligence and Resilience 2 (2023) 100027

Contents lists available at ScienceDirect

Journal of Infrastructure Intelligence and Resilience

journal homepage: www.journals.elsevier.com/journal-of-infrastructure-intelligence-and-resilience

Cloud manufacturing for industrialized construction: Opportunities and challenges for a new manufacturing model

Irfan Čustović [a,b], Jianpeng Cao [b,*], Daniel M. Hall [a,b]

[a] Department of Management in the Built Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, 2628 BL, Delft, Netherlands
[b] Institute of Construction and Infrastructure Management, ETH Zurich, Stefano-Franscini-Platz 5, Zurich 8093, Switzerland

A R T I C L E I N F O

Keywords:
Cloud manufacturing
Industrialized construction
Off-site construction
AEC
Industry 4.0

A B S T R A C T

More widespread use of industrialized construction (IC) is hampered by the high capital cost of advanced production facilities paired with low profit margins. A novel service-oriented cloud manufacturing (CMfg) model could in theory increase utilization and profitability of distributed production facilities. However, little research has investigated how IC can benefit from the CMfg model. This paper examines opportunities and challenges of applying CMfg for IC. First, an adapted model of CMfg for construction is developed based on a literature review. Second, four possible scenarios for applying this adapted CMfg model are designed. Finally, an evaluation is performed through a survey among 25 practitioners and 12 in-depth interviews with industry experts. The paper assesses the desirability and categorizes the benefits and barriers of such a CMfg platform for IC. The results suggest that CMfg could enhance the design quality, support IC suitability assessment for project developers and lower financial risks for off-site manufacturers.

1. Introduction

The architecture, engineering and construction (AEC) sector is characterized by low profit margins and slow adoption of digital technologies compared to the majority of other sectors (Barbosa et al., 2017). As the need for affordable housing is continuously growing, the AEC sector will have to drastically transform and become more efficient. Today, supply chain disruption and increasing material costs are major threats for construction companies' profitability (Hussain, 2022). It is expected that the increased use of information and communication technologies (ICT), assembly of buildings with prefabricated elements as well as an optimization of supply chain logistics will play an important role in overcoming the challenges (Chui and Mischke, 2019; Hussain, 2022). These principles, which are encompassed in the concept of industrialized construction (IC), promise higher quality, lower costs, and better planning reliability (Pan et al., 2012).

However, the adoption of IC on a global scale has not taken place yet, despite encouraging examples from some countries. One hindrance to adopting IC is the large initial capital costs needed to set up specialized factories for prefabrication (Blismas, 2007; Zhang et al., 2018; Wuni and Shen, 2020). Because the specialized manufacturing facilities required for IC are costly, a high utilization rate is crucial to operate them economically. There is need to consider the payback period of expensive software and hardware when planning investments in manufacturing resources, since the cost of purchase could be significant (Goulding and Arif, 2013). However, planning future investments is challenging, as the profit margins of construction companies are low and volatile (Barbosa et al., 2017). Thus, higher upfront costs as well as uncertainty in market demand make it difficult for manufacturers of prefabricated elements to stay profitable and achieve return on investment (Mao et al., 2015; Gan et al., 2018; Agapiou, 2022). There is a need to explore ways to incorporate advanced production facilities into the construction process at lower cost while simultaneously reducing investment barriers for manufacturers.

To increase resource utilization and flexibility of their production systems, the manufacturing industry has transitioned towards manufacturing networks in the last decades. The introduction of cloud manufacturing (CMfg) enables large-scale collaboration of manufacturing operations for the fabrication of complex products (Li et al., 2010). The cloud manufacturing model is based on several preceding manufacturing concepts to enable an efficient organization of distributed supply chains in the wake of globalization. Specific to CMfg is the use of advanced cloud computing, internet of things technologies, and a service-oriented architecture (Liu et al., 2019a). Within the CMfg model, a wide variety of manufacturing resources are encapsulated as services in a cloud platform

* Corresponding author.
E-mail addresses: i.custovic@tudelft.nl (I. Čustović), cao@ibi.baug.ethz.ch (J. Cao), d.m.hall@tudelft.nl (D.M. Hall).

https://doi.org/10.1016/j.iintel.2023.100027
Received 26 October 2022; Received in revised form 20 December 2022; Accepted 20 December 2022
Available online xxxx

(Zhang et al., 2014a). Consumers can access these services on demand to have their desired products fabricated. The cloud system processes customer requirements, matches them to the competitive services and provides the consumer with monitoring of the production progress. The extensive knowledge integrated in the cloud makes it possible to intelligently manage the large-scale distributed manufacturing resources and thereby increase the flexibility of the production system (Rauch et al., 2016; Liu et al., 2019a). This can increase their utilization and make it easier for clients to access innovative production technologies (Tao et al., 2011; Simeone et al., 2019; Lim et al., 2022).

Despite the large interest in the research domain, the CMfg model is still not widely applied in practice and there is a need to improve the assessment of a potential adoption (Zhang et al., 2014b; Yadekar et al., 2016; Jayasekara et al., 2019). Lim et al. (2020) concluded that research should consider the fact that the participation of any company in a CMfg system would depend on particular aspects such as company size, field of activity or market structure. For example, a specific cloud manufacturing system for complex aerospace products was implemented by the *CA Corporation* (Ren et al., 2017). Within the AEC sector, Singh et al. (2021) conducted an early investigation of the CMfg model. They discussed challenges and recommendations for adopting a CMfg platform for 3D printing in construction through the lens of sustainability. However, their research did not address the implications of a cloud manufacturing platform on the products and processes within a construction project. Cao et al. (2021a) proposed a data architecture to model domain-specific knowledge within a cloud manufacturing system for construction. Their work focused mainly on the service matching and resource allocation algorithms.

More generally speaking, we find no research yet that investigates the feasibility of a CMfg model for AEC. This is likely a missed opportunity because CMfg has many potential alignments with the growing trends in IC. The CMfg model is intended to enable an agile production with high resource utilization (efficiency) that satisfies individual client's needs (Yang et al., 2017). Similarly, today's IC is required to deliver unique houses or other structures that fulfill the individual needs of investors and real estate developers at mass production costs (Franke and Schreier, 2008; Jensen et al., 2018). Furthermore, the model is suitable for an application in a short-term collaborative manufacturing environment (Vincent Wang and Xu, 2013). This suggests that it might be applicable in the AEC domain, where individual companies organize themselves around projects (Hall et al., 2020). Therefore, the purpose of this paper is to propose an adapted version of the CMfg model for the AEC sector.

Specifically, the authors have considered the following research questions, which they would like to answer in the context of this paper:

RQ1 – How can the building blocks of the CMfg model be adapted to the AEC sector?
RQ2 – What are possible scenarios in which the CMfg model could be applied to foster adoption of IC?
RQ3 – How can IC benefit from applying CMfg and what are barriers to that?

To answer these questions, this paper investigates both qualitatively and quantitatively the potential application of CMfg in IC. To close the existing knowledge gap, the authors have (1) translated processes, stakeholders and expected benefits of the general CMfg model to the AEC sector, (2) conceptualized potential scenarios of application in a deductive approach and (3) investigated opportunities and challenges that can arise if this manufacturing model was applied. This investigation should enable both researchers and innovative companies from AEC to align their future activities regarding this promising manufacturing model.

The remainder of this paper is organized as follows: Section 2 presents the findings of the literature review of the general CMfg model including stakeholders, operational models, processes and expected benefits. Section 3 explains the research methods used in this endeavor. In particular, the contribution of the individual methods to answering the research questions is presented in more detail. In section 4 the adaptation of the CMfg model to AEC in terms of relevant characteristics and processes is presented. In section 5, the results of the conducted industry survey and expert interviews are described in detail regarding applicability of the CMfg model in IC. In section 6, an analysis of the results is made, and the most important identified opportunities and challenges are discussed. Finally, in section 7, the conclusion of this study is drawn.

2. Background

2.1. General CMfg model

To overcome limitations of preceding concepts and to enable larger-scale manufacturing collaborations focusing on complex manufacturing tasks, the CMfg model was introduced by Li et al. (2010). CMfg promotes a transformation of manufacturing businesses into a large scale, service-oriented, highly collaborative, knowledge-intensive, and sustainable manufacturing network (Tao et al., 2011; Ren et al., 2013, 2015; Wang and Xu, 2014; Wu et al., 2015; Fisher et al., 2018). Important foundations for this concept were seminal developments in the field of *cloud computing* (highly flexible use of powerful computing resources via the internet combined with advanced encryption mechanisms), the *internet of things* (IoT) (connection of physical objects with the internet allowing a continuous data transfer) as well as service-oriented architecture (Tao et al., 2011). According to the CMfg model, manufacturing resources (i.e. machinery, equipment, software) and manufacturing capabilities (i.e. resources, people, knowledge) are transformed into manufacturing services (Zhang et al., 2014a). The services are managed and operated on a central intelligent cloud platform, which enables sharing and circulating of resources within the network (see Fig. 1). Therefore, the platform can manage processes required for seamless collaboration of different companies (i.e. for establishing a virtual enterprise) (Ren et al., 2017). Furthermore, advanced sensing and data transmission techniques are applied in this model in order to dynamically monitor all services in real-time (Ren et al., 2015).

CMfg shares similarities with preceding concepts of distributed manufacturing such as flexible manufacturing or agent-based manufacturing. Due to its broader scope and special focus on resource pooling and cloud computing technology it forms a model of its own (Wu et al., 2014, 2015). A more recent and related concept is cloud-based design and manufacturing (CBDM), which was first introduced by Wu et al. four years after the first publication on CMfg by Li et al. (2010). CBDM has similar requirements and thus uses a similar computing architecture, sourcing processes and business models (Wu et al., 2015). Yet, CBDM focuses solely on the design and fabrication of products. In contrast, already in the initial conceptualization of this manufacturing model, CMfg services are not limited to one particular phase but can address the whole product life cycle including *design-as-a-service* (DaaS), *software-as-a-service* (SaaS), *experimentation-as-a-service* (ENGaaS), *simulation-as-a-service* (SIMaaS), *manufacturing-as-a-service* (MFGaaS), *maintain-as-a-service* (MANaaS) (Zhang et al., 2014a). However, a clear distinction between CMfg and CBDM remains challenging. This is elaborated in a review by Fisher et al. who summarize CMfg as follows: "The cloud manufacturing model is the concept of sharing manufacturing capabilities and resources on a cloud platform capable of making intelligent decisions to provide the most sustainable and robust manufacturing route available" (Fisher et al., 2018).

2.2. Stakeholders

The stakeholders involved in the CMfg concept can be categorized into three groups (Ren et al., 2017): *service providers*, *service consumers*, and *cloud operators*. Service providers are all those who offer their manufacturing resources and capabilities on the platform. These are mainly companies that provide special services within the product life cycle and have the necessary experience to perform these services. Service

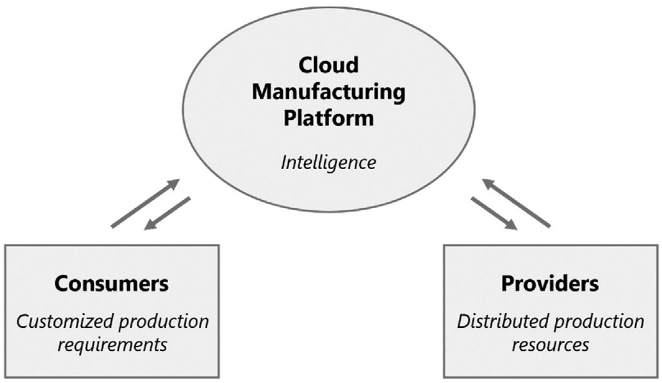

Fig. 1. General concept of CMfg.

consumers can be end-customers as well as other companies. They define product specifications and production requirements and access a broad range of services to operate on any stage of their product life cycle. Cloud operators are responsible for running the platform. This includes maintaining the IT infrastructure, managing access to the platform, and providing applications for enabling interactions, such as registration of services, matching, and billing. They do not provide product-related services for the consumer, nor do they use the services of the providers.

2.3. Operation models

The cloud platform can be implemented with different operation models, depending on the requirements of the stakeholders related to privacy and scope (Tao et al., 2011). A *public cloud* is operated by a third-party provider and allows for a sharing of resources from different enterprises. The responsibility for the services lies solely with the providers. This mode can be especially beneficial for small and medium-sized enterprises, since they do not have to host the IT infrastructure for the platform by themselves, but use dedicated and reliable systems of the operator. However, such an open platform can be incompatible with an enterprise's safety and privacy requirements.

A *private cloud* is independently operated by an organization and only allows sharing of its services. Thus, it is possible for an organization to control the platform according to its needs since it is responsible for both the infrastructure and the service offering. One such organization can be, for example, a consortium of companies that want to share manufacturing resources among themselves and among their subsidiaries. Nonetheless, hosting a cloud independently is linked with high cost and requires additional effort.

A *hybrid cloud* can be seen as a combination of a private and a public cloud. In this mode, some services and information can be hosted within private clouds and other, non-critical services can be integrated into a public cloud and offered to third party consumers. As such, the hybrid mode can link several private clouds with a larger public cloud enabling various levels of interaction.

2.4. Process structure

Ren et al. (2013, 2017) describe the processing of orders via the cloud platform in four steps and specifically address the activities of the individual stakeholders (see Fig. 2).

In step 1, the services are registered in the cloud and the customer requirements are transmitted. For the registration process, the manufacturing resources are virtualized using IoT technology and published with their specific capabilities in the service pool of the cloud platform. The service consumer then submits its customized requirements, which can be either final product designs or individual manufacturing tasks.

In step 2, consumer requirements are matched with available services. Based on the knowledge modeled on the platform, many parameters, such as task description, payment conditions, physical location, and service performance indicators, are evaluated to achieve intelligent matching. Subsequently, consumers can renegotiate the exact conditions with the providers and form a virtual alliance.

In step 3, the services are executed to satisfy the requirements defined by the customer. If these are virtual services, such as the provision of software, all management takes place via the cloud platform. Otherwise, if the services are physical services outside the cloud, such as the processing of products by personnel or machines, the order is placed, and the work progress is monitored via digital communication interfaces. In both cases, the cloud makes it possible to adapt the virtual organization as needed without any particular effort by the participants. For example, if a machine breaks down, the production order can be routed to another service. In the end, the consumer receives the deliverables requested.

In step 4, the services are evaluated and billed. The evaluation can consider measured performance indicators during service execution and subjective ratings (Ren et al., 2013). For billing, the platform records the particular service capacities actually consumed, such as the computing power used to perform numerical analysis of a piece, or the effective amount of material used for 3D printing it. These capacities are invoiced according to predefined terms and conditions.

2.5. Expected benefits of applications

Scholars and initial industry applications suggest that CMfg offers multiple advantages for the manufacturing industry (see Table 1). Research indicates that the large-scale sharing of services within a CMfg network can increase the utilization rate of manufacturing resources (Tao et al., 2011; Wu et al., 2015; Li et al., 2018; Simeone et al., 2019; Lim et al., 2022). Further, a CMfg system can provide companies with access to innovative manufacturing technologies without the need for high investments (Tao et al., 2011; Wu et al., 2014; Mourad, 2018; Fast Radius Inc., 2021a; Fictiv Inc, 2022b; Xometry Inc., 2022b). Moreover, several works suggest that the combination of distributed resources within an intelligent central platform can increase the flexibility of manufacturing systems in order to react efficiently to different demands (Tao et al., 2011; Zhang et al., 2014a; Rauch et al., 2016; Liu et al., 2019a; Fast Radius Inc., 2021a; 3D HUBS B.V., 2022). Liu et al. (2019b) point out that CMfg has the potential to make the usage of knowledge within production systems more efficient. In particular, the flow of product design information can be improved through standardized communication with the cloud platform (Mourad, 2018). In this regard, intelligent manufacturability analysis and automatic matching of customized requests with available services via the platform can lead to better integration of design and manufacturing (Wu et al., 2015; Ren et al., 2017; Fast Radius Inc., 2021b; 3D HUBS B.V., 2022; Xometry Inc, 2022b). Besides, the real-time monitoring of services provided by the

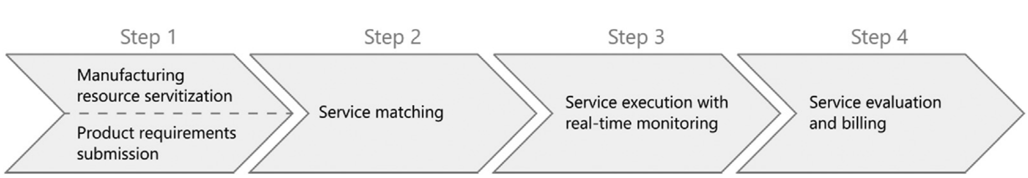

Fig. 2. Process structure of the general CMfg model.

cloud system can increase transparency within the supply chain (Zhang et al., 2014a; Liu and Xu, 2017; Liu et al., 2019a; Fast Radius Inc., 2021a; Wei et al., 2021).

3. Methodology

The research for development of the CMfg framework for AEC follows a deductive approach (Creswell, 2013; Muñoz-La Rivera et al., 2021) and it is conducted in three phases (see Fig. 3). Detailed description of research tools, activities and deliverables in each phase is presented below.

3.1. Phase 1 – Analysis of the general CMfg model

In the first phase, a content analysis of literature review was conducted. This was done to identify and compile the building blocks of the general CMfg model and to determine expected benefits of its application in practice. Relevant research was reviewed querying Google Scholar with the keywords "cloud manufacturing" , "cloud-based manufacturing" and "cloud-based design and manufacturing". Therefore, all papers that were not specifically related to the building blocks and its application in practice were removed from investigation. Result of this phase was a listing of key stakeholders, operational models as well as expected benefits suggested in research or early industry applications of the CMfg model, as presented in section 2 above.

3.2. Phase 2 – Adaption of CMfg to IC

The second phase focused on a deductive analysis of the literature findings for an adaption of the general model of CMfg to the circumstances of a construction project (*RQ1*). Thereby, the building blocks of CMfg were identified and adapted to the context of construction projects. Further, the process structure was adapted including the roles of the project participants, the sequence of their interactions as well as domain-specific ICT usage.

Next, four scenarios in which the CMfg model could be used in the context of the AEC sector were conceptualized (*RQ2*). These scenarios target particular services and life cycle phases relevant to IC. In the last step of this deductive analysis the authors compiled a list of potential benefits and barriers, that could arise during future implementation of the model in construction (*RQ3*) building upon the deliverables of phase 1 (see Table 1).

3.3. Phase 3 – Evaluation of opportunities and challenges

In the third and final phase, a mixed methods research approach was chosen to evaluate potential opportunities and challenges that could arise in the course of implementing CMfg in a real construction project. Conducting an industry survey and expert interviews, the benefits and barriers of the developed model were to be identified (*RQ3*) and finally the suitability of the scenarios was to be investigated (*RQ2*). This combination of quantitative and qualitative methods makes it possible to obtain a broader scope of findings and increase the significance of the results compared to when only a single method is applied (Johnson and Onwuegbuzie, 2004).

3.3.1. Industry survey

The survey consisted of four parts. In part 1 of the survey, participants were asked about their background as well as their previous involvement in projects applying prefabrication. In part 2, the participants were introduced to the general CMfg, provided with application examples from the traditional manufacturing industry, and shown the adapted model for IC. This was to ensure a basic understanding about the topic and to assure the validity of the answers given. In part 3 of the survey, participants were asked to rate the 4 developed scenarios in terms of desirability. For this purpose, the scenarios were introduced with short descriptions and a rating was requested using a Likert scale (1 – *Very undesirable*, 5 – *Very desirable*). In part 4, participants were also asked to assess the likelihood of 7 possible benefits and 8 potential barriers using Likert scales (1 – *very unlikely*, 5 – *very likely*/1 – *no barrier*, 4 – *large barrier*). Furthermore, the participants had the option to indicate "I don't know" as an answer. At the end of the survey, it was possible to provide further comments.

Before publication, the questionnaire was tested with three researchers in the field of IC and digital technologies. On this basis, the questionnaire was finalized and translated from English to German in order to increase the possible range of answers, especially in the German-speaking countries. During the evaluation, the answers of both language versions were summarized.

The survey was distributed via social media as well as subject-specific e-mail distribution lists. Since the survey was distributed randomly via various channels, a direct number of recipients cannot be determined. Instead, the number of clicks on the survey links was captured. The survey was accessed a total of 220 times (179 English, 41 German) and completed 25 times (22 English, 3 German). This corresponds to a response rate of 11.3%.

Fig. 4 shows the professions of the participants. Industry professionals make up the largest proportion with 18 participants (72%) and are

Table 1
Potential benefits of CMfg application as indicated by academia and industry examples.

Expected benefit of CMfg	Research suggesting this benefit	Industry application promoting this benefit
Increased manufacturing resource utilization	(Tao et al., 2011) (Simeone et al., 2019) (Lim et al., 2022) (Wu et al., 2015) (Liu and Xu, 2017)	(Fictiv Inc, 2022a) (Xometry Inc, 2022a)
Easier access to innovative, capital-intensive technologies	(Tao et al., 2011) (Wu et al., 2014 (Mourad, 2018)	(Fast Radius Inc., 2021a) (Xometry Inc, 2022b) (Fictiv Inc, 2022b) (Beelse, 2021)
Increased flexibility of the manufacturing system regarding varying customer demands	(Liu et al., 2019a) (Zhang et al., 2014a) (Rauch et al., 2016) (Tao et al., 2011)	(Fast Radius Inc., 2021a) (3D HUBS B.V., 2022)
More efficient knowledge management	(Liu et al., 2019a) (Mourad, 2018)	(Fast Radius Inc., 2021a)
Better integration of manufacturing constraints into product design	(Ren et al., 2017) (Wu et al., 2015)	(Xometry Inc, 2022b) (3D HUBS B.V., 2022) (Fast Radius Inc., 2021b)
Increased transparency within the supply chain	(Liu et al., 2019a) (Zhang et al., 2014a) (Liu and Xu, 2017) (Wei et al., 2021)	(Fast Radius Inc, 2021a)

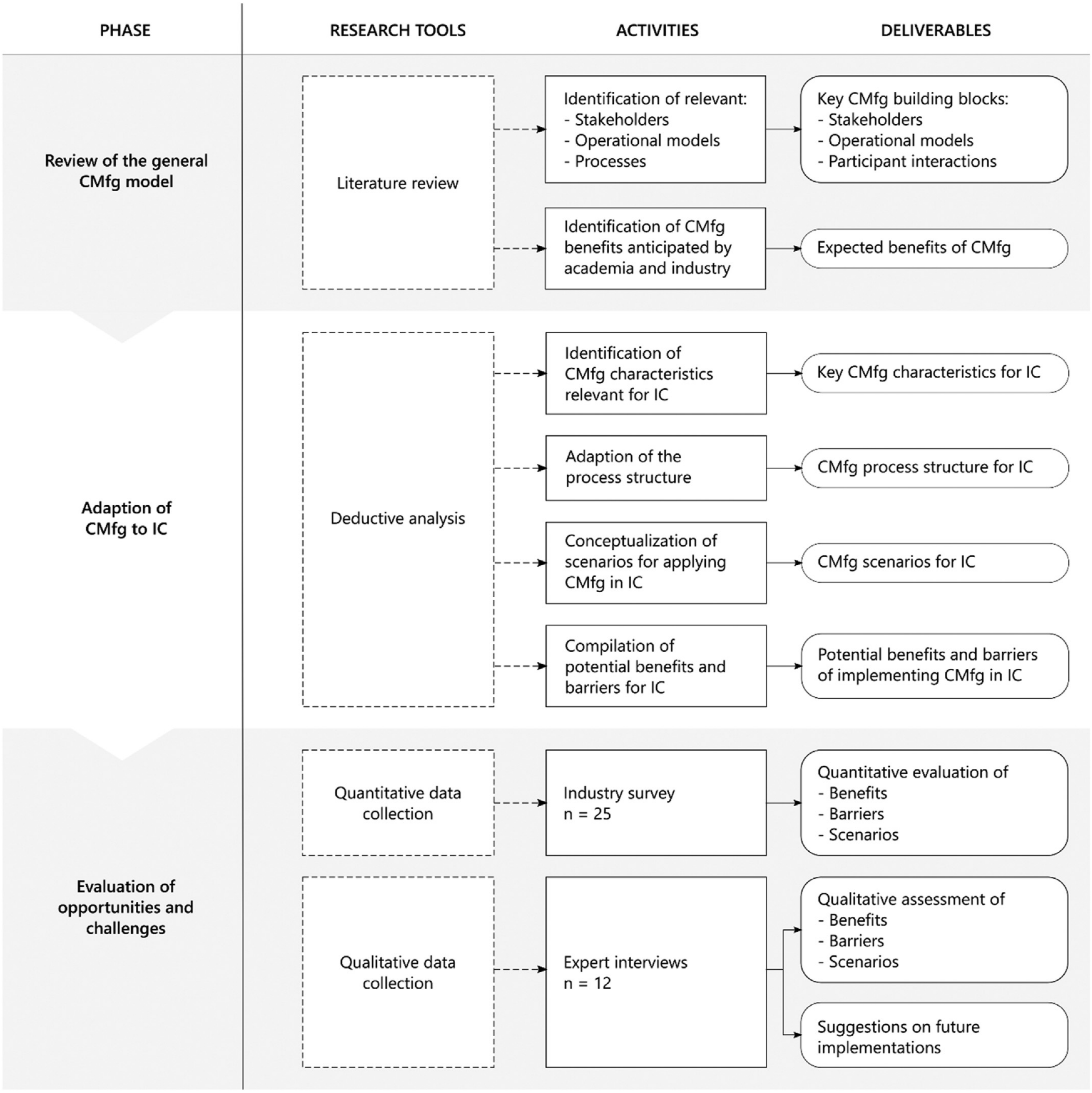

Fig. 3. Research methodology.

distributed among various professions that represent a broad spectrum of AEC stakeholders. The remaining participants are distributed among various professions that represent a broad spectrum of AEC stakeholders. In addition, three participants indicated that they worked in more than one of these roles without specifying this more precisely. Regarding the previous experiences with IC, around one third of the survey participants worked on more than 10 projects, which enhances the validity of the survey results (see Fig. 5). Of the three participants that did not work on any projects with IC, two were researchers.

3.3.2. *Expert interviews*

To obtain a qualitative assessment of the CMfg model for IC a total of 12 semi-structured interviews were conducted in January 2022. The sample of interviewees consists of people representing various stakeholders in a construction project (see Table 2). On the one hand, they were contacted by the authors' assessment of their relation to the topic based on their previous occupation in the AEC domain and, on the other hand, they had the opportunity to voluntarily express their interest in a more in-depth interview during the survey.

The interviews were scheduled for 45 or 60 min but could be extended if the participants were interested. In total, 12.25 h of interview material were gathered. After a short welcome, the first 15 min were spent familiarizing the participants with the CMfg model, helping the interviewees to comprehend the purpose of this research. A slide presentation was used to explain the general model in the same way as for the survey (see section 3.3.1), to present the customized CMfg model for

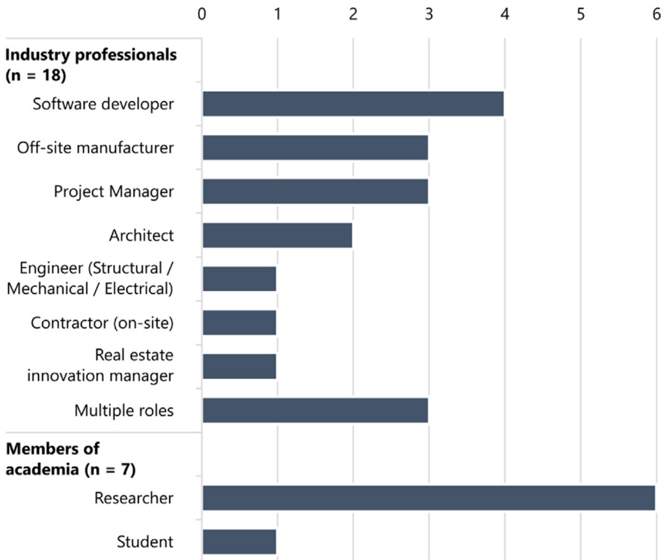

Fig. 4. Professions of the survey participants. n = 25.

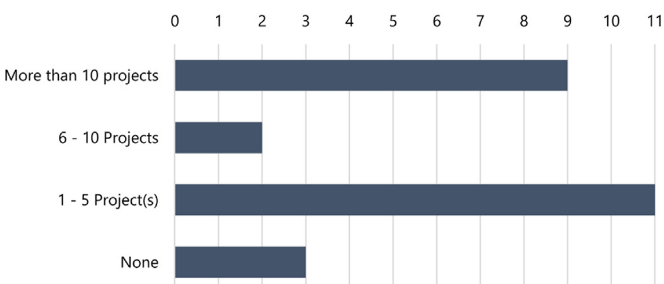

Fig. 5. Previous involvement of participants in projects where IC was applied. n = 25.

IC, and to present four possible scenarios. The interviewees had the opportunity to ask questions at any time to avoid ambiguities. In the remaining time, the interviewees shared their opinion on the scenarios, possible advantages, and any obstacles. To this end, they were asked which scenarios they considered most beneficial to the current AEC sector, as well as open-ended questions about any characteristics of the proposed CMfg model. In some cases, queries were made about particular advantages or barriers.

The thematic analysis was based on descriptive coding (Saldana, 2013) and was conducted with the text analysis software MAXQDA (VERBI GmbH, 2022). For this purpose, first the interviews were transcribed and then pertinent statements were assigned two kinds of codes. The first code refers to the statement topic addressed and was derived from the important characteristics of CMfg. The second code refers to the category of the statement, i.e., whether it is a benefit, a barrier, or a future perspective. Individual statements can be assigned several codes per kind of codes. Based on this thematic analysis, conclusions were drawn whether characteristics of the CMfg model for IC can yield benefits or encounter barriers.

4. Findings: the CMfg model for IC

4.1. Characteristics of the CMfg model for IC

Based on the findings of the literature review and the deductive analysis, six CMfg characteristics have been identified and compiled into an adapted process structure for IC. They include (I) *manufacturing resource pooling*, (II) *comprehensive knowledge management*, (III) *standardized requirement definition process*, (IV) *manufacturing service encapsulation*, (V) *intelligent service matching & quotation* and (VI) *real-time service monitoring with IoT*. A detailed description of the characteristics can be found in Table 3.

4.2. Process structure of the CMfg model for IC

The process structure for handling an order within the general CMfg model (cf. section 2.4) was adapted to the constraints of construction projects and is depicted in Fig. 6. Here, the key stakeholders comprise architects and general contractors (*consumers*) as well as off-site manufacturers and providers of digital fabrication robotics (*providers*). In this case, the cloud system is public and allows various consumers or providers to participate.

In the first step the machines are encapsulated as services on the cloud. Specific information about the task they can perform (e.g., stud framing), the duration it takes to do this and the costs that arise from this need to be specified. When a consumer wants to order an element to be prefabricated, they upload a file to the platform. Ideally, the file can be a high level of detail (LOD) BIM, which is commonly used in the industry. The system can validate the files regarding the syntax and assess the manufacturability of the element by extracting element properties and check it against the regulations, available machinery and personnel capabilities registered on the cloud. If improvements are required in order to make it manufacturable or to comply with building codes, the consumer will get immediate feedback. Otherwise, the cloud platform will match these requirements to specific manufacturing services. The results include a list of potential off-site manufacturers that can perform the necessary work as well as detailed cost and time estimates. After the consumer has decided to order the production via the CMfg platform, the system manages the fabrication process. This includes automatic generation of bill of materials and task dispatching to determined machinery via production planning systems, without a need for the manufacturer to remodel or derive manually production orders from the BIM file. While the services are performing their work, the cloud platform receives periodic updates on the production process via IoT. This enables the system to measure the performance of a service, to react to unexpected disruptions during execution and to provide real-time status updates to the consumer. This evaluation is stored in the cloud to improve the matching accuracy and detect abnormal quotations through comparison based on historical data. Thereby, the platform prevents service providers from intentionally understating the durations and costs of their services. Upon completion of the services, the cloud platform manages the logistics of the product - either to the construction site or to the location of succeeding services.

4.3. Potential application scenarios of CMfg in construction projects

The scenarios were designed to showcase the application of CMfg services relevant to IC. In general, the service offering in a CMfg extends over the whole life cycle of a product. Yet, the focus of this study is to foster the integration of advanced production facilities into the construction process. Therefore, the scenarios are targeted at the design, planning and execution phases. Scenario A was designed with the intent of promoting the use of digital planning tools through a CMfg platform in the early design stages. Scenarios B and C illustrate a possible application of the cloud platform in the context of the planning of buildings and differ with regard to the implementation depth of the encapsulation and matching characteristics. Scenario D covers the use of the cloud platform for placing orders and managing production during project execution.

A) **Modeling/analysis/scheduling/… software provision on demand**

Software developers deploy their applications on the cloud platform (e.g., BIM design tools, life cycle analysis (LCA) software, product configurators) (Fig. 7). Consumers can order access to this software on

Table 2
Overview of respondents designated by their profession and years of industry experience.

Profession	Focus area	Industry experience
Architect	Building information modeling	15 years
Consultant	Building information modeling	15 years
Consultant	Digital data for construction	11 years
Consultant	Off-site construction	10 years
Consultant	Project Management	7,5 years
Consultant	Supply chain and procurement	6 years
Industrial robots manufacturer	Element construction industry	7,5 years
Real estate developer	Building information modeling	9 years
Researcher	Digital fabrication	4 years
Researcher	Digital fabrication	6 years
Software developer	Building systems design platforms	17 years
Software developer	Design data and modeling tools	7 years

demand and instead of purchasing a long-term license, each time the application is used, a small per-use subscription fee must be paid. The cloud platform manages access control and payment. Although this scenario is not aimed at machine sharing, it was conceived since making domain-specific software available could be conducive to higher data quality in construction projects.

B) **Preliminary quotation on project cost & duration**

Off-site manufacturers provide approximate information on (i) what kind of task they perform (e.g., wall panels, modular elements) (ii) how they create cost estimates (e.g., element volume X unit price), and (iii) how long expected lead times are (Fig. 8).

Designers upload a low LOD BIM file of the product (e.g., interior wall panel). At this LOD, the product is represented as a generic object with a rough size, shape, location and orientation. The cloud platform validates the file, extracts simple information (e.g., volumes, surface areas) and identifies potential manufacturers who can fabricate the product. Based on that, the cloud platform provides the consumer with a list of suitable manufacturers with approximate cost estimates and lead times. Upon evaluation of the suggested services and based on prior experience in collaboration with specific providers, the consumer can choose his preferred service.

C) **Manufacturing service suggestion**

Off-site manufacturers encapsulate their manufacturing resources (e.g., machinery, workstations) as services in real-time in the cloud (Fig. 9). This includes specific definition of (i) which tasks a resource can perform (e.g., cutting, framing, stud fitting), (ii) for what kind of product (e.g., small-sized panels, whole modules), (iii) how much time these operations take and (iv) how much costs arise while performing the operation.

Designers upload a high LOD BIM file of the product (e.g., wall panel). At this LOD, the product is represented as a specific assembly with detailed size, shape, location and orientation alongside information on fabrication, assembly and installation. The cloud platform validates the file, extracts detailed information (i.e., sub-components, connections, installations) and automatically identifies which services are required to fabricating the product. Based on that, the cloud platform provides the consumer with a detailed list of services that can be used to fabricate the desired product alongside with a detailed cost and time estimate.

D) **Manufacturing order placement and production progress monitoring**

The consumer uploads a high LOD BIM file to the platform and selects a specific manufacturer to produce the desired product (Fig. 10). The platform assigns tasks to the corresponding manufacturing services, creating detailed production orders grounded on its detailed knowledge

Table 3
Characteristics of the CMfg model for IC.

Characteristic	Description
I – Manufacturing resource pooling	The major characteristic of CMfg is to facilitate efficient sharing of manufacturing resources. This is made possible by integrating a variety of resources such as machines, tools, or software from different plants and/or companies centrally on one platform. Consumers can then access the services of these resources easily on demand, depending on their specifications, and only pay for the service actually used. In this sense, scholars have investigated the application of eCommerce platforms in construction (Grilo and Jardim-Goncalves, 2011; Raju and Feldman, 2020; He et al., 2018). It was found that platforms can be beneficial for increasing competitiveness and coping with fluctuations (Raju and Feldman, 2020). Yet, data formats require industry-specific consideration (He et al., 2018).
II – Comprehensive knowledge management	Knowledge management plays a key role in the performance of a CMfg system to ensure both an efficient operation of the platform itself and the long-term competitiveness of companies regarding their product offering. Extensive knowledge about the services (i.e., production process) as well as customer requirements (i.e., product specifications) is managed, linked, and evaluated to achieve efficient production with the resources available in the network. Similarly, in IC projects the reuse of experience and continuous management of performance indicators from all participating companies is of high importance for success (Lessing et al., 2005). In this regard, the usage of intelligent Building Information Modeling (BIM) platforms can be useful for generating knowledge by storing, linking, and evaluating the data generated from the various stakeholders involved (Li et al., 2019; Werbrouck et al., 2022).
III – Standardized requirement definition process	In search for suitable production services, consumers need to upload their requirements to the platform. Here, standardized electronic data interchange formats are used in order to enable the cloud system to automatically interpret the inputs. In IC projects, BIM models are the de-facto standard for describing the objects to be built (Sacks et al., 2018). Although the Industry Foundation Classes (IFC) are the dominant data model for BIM information exchange, in recent years semantic web technologies proved to be beneficial for defining building products specifications (Kalemi et al., 2020).
IV – Manufacturing service encapsulation	Within the CMfg model, it is envisaged that all manufacturing resources and capabilities will be encapsulated in the cloud. Thus, for hard resources such as machines or tools, the particular operations which they can perform, as well as the associated costs and time spans, are documented. In IC it is crucial to bring the constraints of downstream activities to the upstream design phase as mistakes in early project stages lead to severe delays when only identified during production. Academia and research has found configurators to be beneficial for this issue, although not representing the capabilities of an individual machine but rather the products that can be fabricated (Cao et al., 2021a). Yet, this sharing of detailed manufacturing information with other stakeholders requires mechanisms to ensure transparency, privacy-preservation and immutability (Li et al., 2021).

(*continued on next page*)

Table 3 (*continued*)

Characteristic	Description
V – Intelligent service matching & quotation	The CMfg system uses extensive knowledge of product requirements and service capabilities to run algorithms that intelligently match consumers and producers. In doing so, the platform can identify services that are necessary for production, predict the costs to be incurred and determine estimated fabrication times. Early studies have developed algorithmic solutions for matching design intents of architects with capacities of off-site manufacturers (Cao et al., 2022) as well as creating work packages for automated production planning (Li et al., 2022b; Skoury et al., 2023).
VI – Real-time service monitoring with IoT	An enabling characteristic of CMfg is a ubiquitous sensing of manufacturing resources through IoT technologies. They include radio frequency identification (RFID), bar codes, QR codes, GPS trackers, embedded systems as well as Wi-Fi, 4G, and 5G communication standards. The status of a service as well as the production progress of the orders can thus be monitored. Monitoring the production and assembly ensures that the expected financial and temporal benefits of IC over bespoke on-site construction can be achieved. Prior studies have demonstrated how IoT technology helps in this regard (Zhong et al., 2017; Li et al., 2022a).

of each service. The manufacturer does not need to interact with the customer or to perform manual work preparation (i.e., remodel elements for planning the production, generate a bill of materials). Furthermore, the cloud platform provides real-time status information on the production process to the consumer through an IoT based monitoring.

4.4. Potential benefits and barriers of implementation

The deductive analysis included a compilation of potential benefits alongside potential barriers. The seven benefits are an easier integration of digitally enabled manufacturing technologies, a long-term learning and process improvements for IC, a streamlined data flow from design to manufacturing, a broader spectrum of prefabricated products offered, an easier assessment of IC suitability in early project phases, an increased design quality through design for manufacturing and assembly (DFMA) feedback, and a lean synchronization between fabrication process and on-site assembly (see Table 4). Eight potential barriers include a poor data quality, the risk of shifting of competitive advantages, contractual issues with existing legal frameworks, a less direct interactions of planners and manufacturers, a low digitalization of production facilities, high cost for implementing IT equipment, and high cost for training personnel (see Table 5).

5. Evaluation

5.1. Benefits and barriers of the CMfg model for IC

The survey revealed a long-term learning process, a greater design quality as well as an easier assessment of the suitability of prefabrication to be the most likely benefits (see Fig. 11). At the same time, they identified the existing contractual framework, an insufficient network of companies, and a threat to their competitive advantage as the most significant barriers (see Fig. 12).

Supplementary to this, through the interviews it was possible to identify further benefits and barriers and to link them more specifically to the individual CMfg characteristics.

I **Manufacturing resource pooling**

Several interviewees share the opinion that resource sharing through such a platform can increase the performance of machines and will make it easier for manufacturers to acquire them. In this context, interviewees see an easier integration of advanced digital manufacturing technologies as a possible advantage. This assessment is also reflected in the results of the survey, according to which 17 out of 25 participants (68%) believe this is likely or very likely. Furthermore, participants believe that manufacturers will be able to better balance their workloads and accept larger orders. One respondent states that a larger network of production facilities could lead to increased sustainability by optimizing transport routes.

Respondents see multiple barriers to achieving resource sharing. For example, it was stated several times that the design regulations in

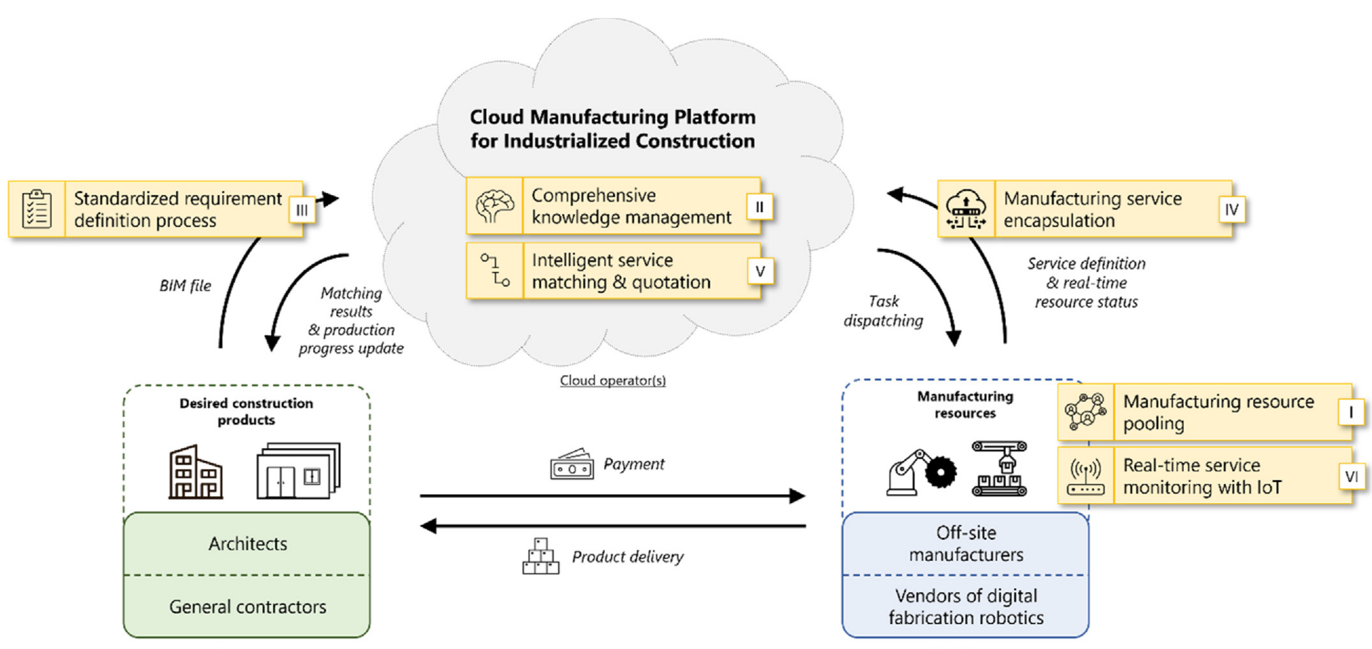

Fig. 6. Process structure of the CMfg model for IC.

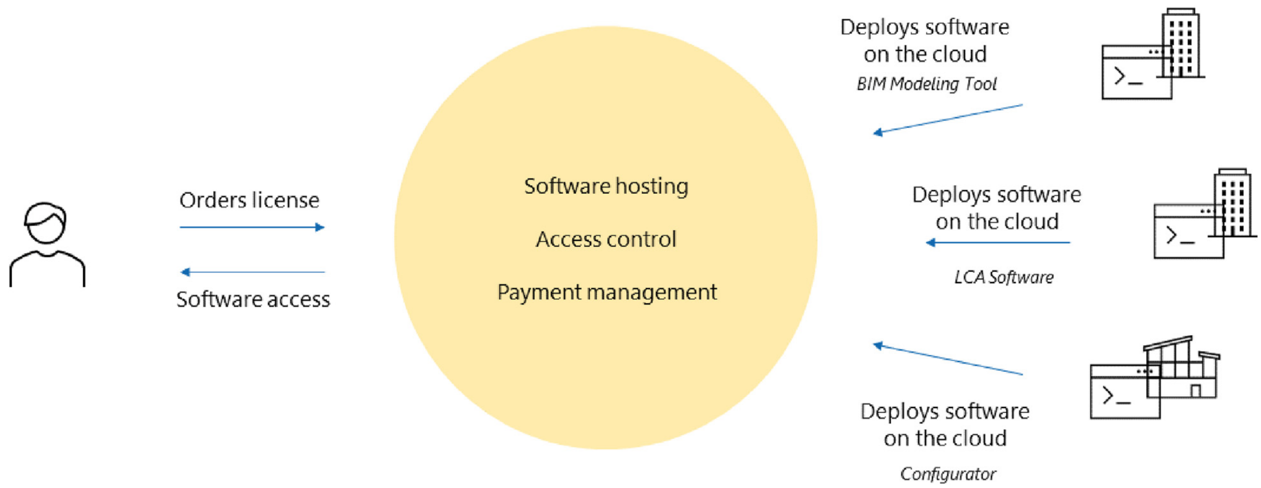

Fig. 7. Scenario A – Modeling/analysis/scheduling/… software provision on demand.

different places may be an obstacle to achieving full resource sharing, because these make it difficult for manufacturers to produce for markets, they are not familiar with. This contractual aspect is also mentioned as an obstacle by all survey participants, with 48% seeing it as a large barrier. Besides, large manufacturers of precast elements may be reluctant to make their resources available to other market participants, preferring to prioritize their own orders. In this regard, 96% survey participants assess the number of service providers on a potential platform as a barrier (32% as a large barrier). Lastly, one respondent states that the size of the parts to be manufactured makes it economically and physically challenging to transport them between different factories and to the construction site.

II **Comprehensive knowledge management**

Interviewees indicate that sharing data and knowledge via such a platform would be beneficial. Knowledge management could improve the exchange of information between stakeholders in a project. If knowledge was publicly available, this could provide valuable insights to stakeholders and enable long-term learning. 80% of the survey participants also see this as likely or very likely.

However, it was noted that it will be a challenge to adapt the CMfg system and the knowledge contained to different local legislation and approval procedures. A barrier to this shared knowledge may also be the risk of losing one's competitive advantage, as viewed by most survey respondents (96%), with 40% seeing it as a large barrier. One respondent sees a possibility for the future in storing legal requirements in the product details or in the definitions of the capabilities of individual services.

III **Standardized requirement definition process**

From the interviewees' statements, it is evident that a CMfg system would be beneficial for processing the design data. Making selected planning tools available via the cloud could both improve the quality of designs and standardize the methodology of planning. If the data is transmitted in a completely transparent manner, this can reduce the effort required by manufacturers for remodeling. In addition, one of the interviewees comments that this standardization would simultaneously make it easier to integrate digital means of production into the construction processes. A large proportion of the survey participants shares the opinion that a smaller effort for manufacturers and an easier integration of digital production equipment are potential (see Fig. 11). Nevertheless, at the same time 5 survey respondents (20%) think that the remodeling effort will not likely be reduced by a CMfg system.

Various potential barriers in this regard are addressed by the interviewees. At present, the quality of the design data seems to be simply too inadequate. This is also seen as a barrier by a large majority (84%) of the survey participants, with 36% seeing it as a large barrier. In this regard, interviewees point out that architects would have to be trained to create such high-quality models. Otherwise, it would be required to

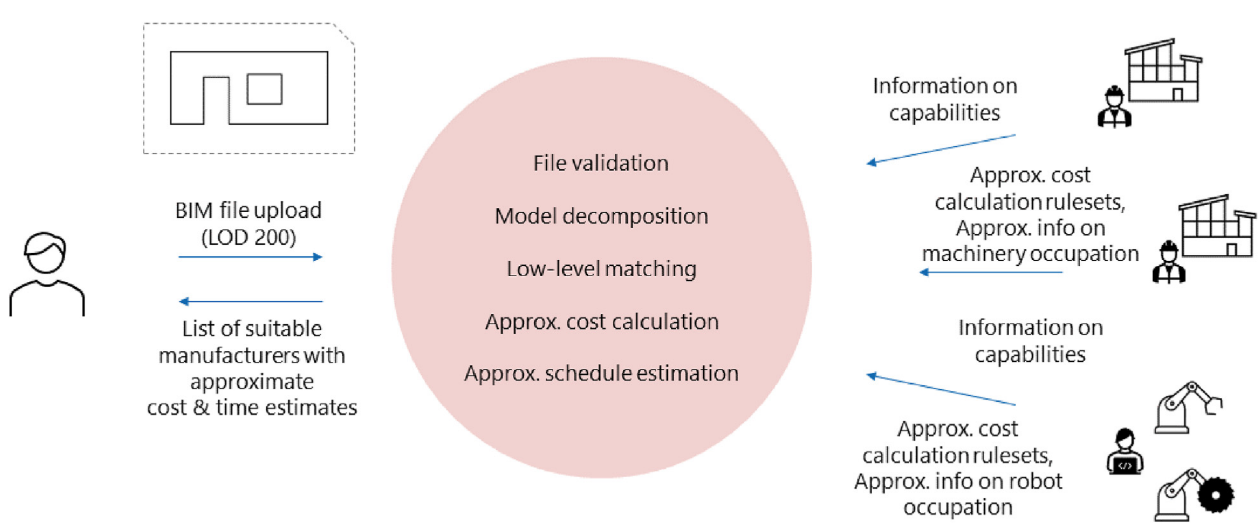

Fig. 8. Scenario B – Preliminary quotation on project cost & duration.

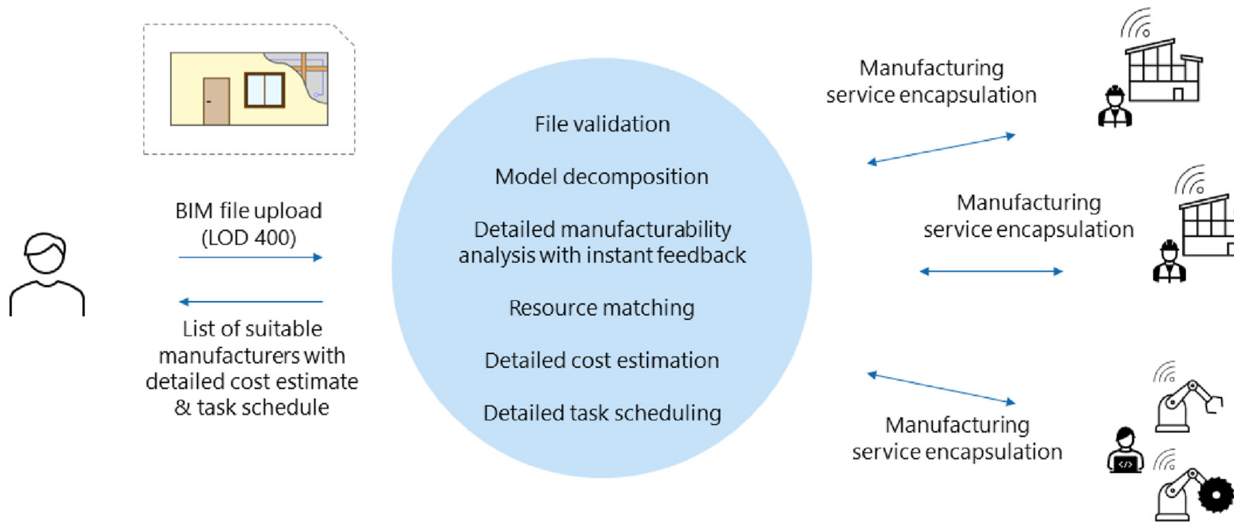

Fig. 9. Scenario C – Manufacturing service suggestion.

develop algorithms to translate the design into production automatically, which is assessed difficult by several interviewees.

IV **Manufacturing service encapsulation**

Several interviewees consider it twofold advantageous to integrate the manufacturers' offering scheme in the form of services into a CMfg system. On the one hand, it would be useful to planners when developing building designs. They could get a comprehensive view of the solutions/services available on the market at an early stage without having to commit (financially) to a particular contractor. Likewise, 18 survey respondents (72%) think that a CMfg system would likely or very likely make it easier for planners to assess the suitability of prefabrication for a project. On the other hand, it would be economically advantageous for manufacturers, because they would not be limited to their own sales channels but would have greater reach. They could focus on clients' specific requirements, prioritizing more worthwhile jobs. In addition, the simplified processing via the platform would enable them to save costs for conventional sales.

Nevertheless, during the interviews a lot of barriers regarding this characteristic were pointed out. Multiple respondents highlight that it requires very specific knowledge to digitally reflect the capabilities of manufacturers on such a platform. This is not part of a manufacturers' expertise and current business model. Accordingly, another interviewee notes that in substantial market segments such as precast concrete parts, there is a lot of price pressure and manufacturers are not willing to share their offer publicly (with their competitors) via such a platform. This could be even more critical for innovative companies, comments another respondent. These findings are in line with the 96% of respondents who believe that sharing know-how could be detrimental to a manufacturer's market position.

V **Intelligent service matching & quotation**

Many participants see an intelligent analysis of design drafts with direct feedback to the planners in terms of manufacturability as a particular advantage of a CMfg platform. This feedback would improve both design quality and data quality. In the survey this benefit was rated second most often as likely or very likely (76%). For example, one interviewee states that the cloud platform could provide immediate feedback on feasibility. Thereby, planners could focus more on the design intent instead of definite manufacturing-related details. In addition, automatic generation of cost and time estimates in an early design stage would be very beneficial, according to several respondents. This would

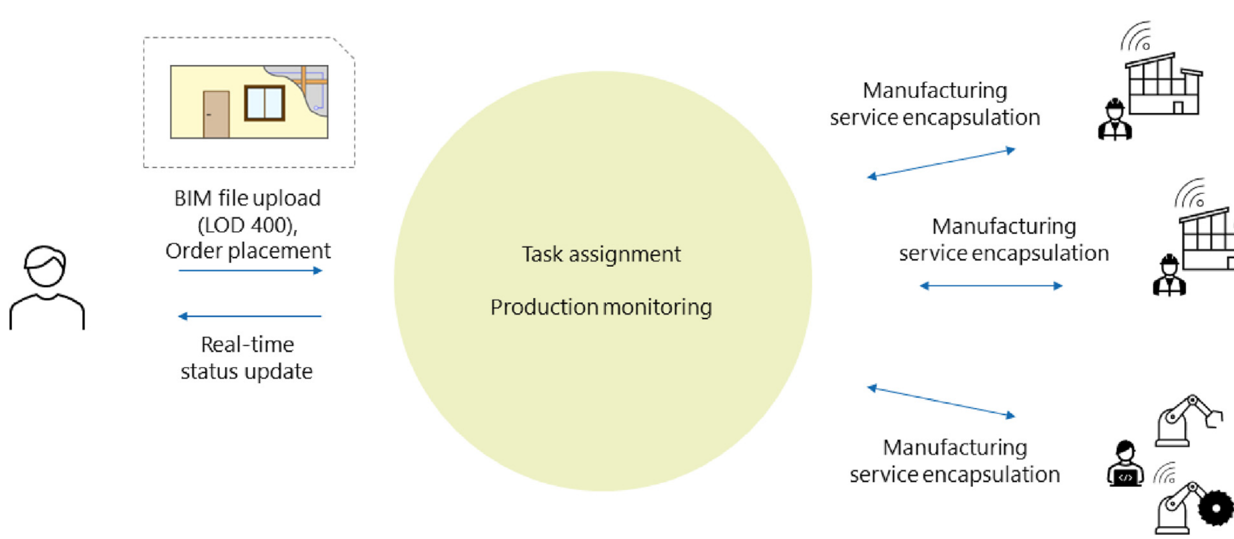

Fig. 10. Scenario D – Manufacturing order placement and production progress monitoring.

Table 4
Potential benefits of implementing the CMfg model in IC.

Benefit	Description
Easier integration of digitally enabled manufacturing technologies	The platform can promote the adoption of digital manufacturing technologies by lowering the threshold for expensive fabrication equipment. For one, sharing of manufacturing resources over the platform can increase the machinery utilization. For another, various investors and contractors can easily make use of advanced equipment on a pay-per-use basis without buying it.
Long-term learning and process improvements for IC	The cloud platform can serve as a central point of access for a wide range of construction knowledge, prevent information silos and thus improve processes on the long-term. Standards and regulations, specific knowledge on best practices regarding construction methods as well as historical analyses of the services' performance can be stored and made available to a variety of project participants.
Streamlined data flow from design to manufacturing	The CMfg system could reduce the effort for manufacturers to remodel elements for planning the production with their systems. If the details of the products to be fabricated are submitted using standardized data formats, manufacturing-relevant information can be extracted immediately. Using intelligent algorithms on the cloud system, this data can be exploited to directly create detailed production orders for importing into the machinery software.
Broader spectrum of prefabricated products offered	Planners could be more flexible in their designs and search more easily for manufacturers that can fulfill their specific product requirements. As many different manufacturing resources would be encapsulated in a single cloud platform, they would not have to constrain their designs to the capabilities of a small number of manufacturers they have worked with before.
Easier assessment of IC suitability in early project phases	The service matching performed by the cloud system could make decision-making more verifiable, as it provides a preliminary assessment of feasibility, expected costs and production times. These objective indicators can enable planners to evaluate the suitability of IC for a project at an early stage.
Increased design quality through DFMA feedback	The quality of designs could be improved by implementing a CMfg platform. After requirement submission, the integrity of the model can be checked in terms of the syntax but also regarding manufacturability. Such an automatism can enable feedback loops and allow for model optimization at an early stage, without the need to wait for a manufacturer's assessment.
Lean synchronization between fabrication process and on-site assembly	The real-time monitoring of services can improve synchronization between production and assembly on the construction site. In case of delays, other manufacturing processes can be rescheduled intelligently to avoid storage buffers.

significantly improve the accuracy and reliability of estimates, also compared to (subjective) expert opinions. Planners could better understand the effects of adjustments during the design process. In the long term, one of the respondents even sees the possibility of increasing the accuracy of estimates by incorporating historical measurement of service performance.

At the same time, barriers are pointed out that would have to be overcome to implement such a feature. One respondent states that poor data quality hinders such service matching and quotation, as extensive details have to be represented digitally to enable these calculations. Furthermore, two respondents state that manufacturers would not be interested in sharing detailed knowledge about their production processes. Again, this is consistent with survey respondents' assessment that sharing knowledge on a CMfg system could threaten competitive advantage. In addition, the myriad of different legal regulations and standards in different regions would be a particular difficulty. Finally, if manufacturability was not 100% assured, the estimates generated by the cloud platform would be worthless, state multiple respondents.

VI **Real-time service monitoring with IoT**

In the course of the interviews the introduction of real-time monitoring was assessed as beneficial for IC. According to two interviewees, it would enable on-site teams to adjust their work schedules to the expected delivery of components and thus meet deadlines better. At the same time, the project team could better assess the extent to which subsequent changes affect the project and the costs. To this end, one of the interviewees noted that it would not be necessary to solely rely on the assessment of individual staff, but rather have a sound data record in the event of delays, for example. Although better synchronization was also rated as likely or very likely by 14 participants (56%) in the survey, it is nevertheless one of the least likely benefits identified.

Yet, respondents point out that there are barriers to the introduction of such monitoring in AEC. Multiple respondents believe that many of the manufacturers do not have the necessary equipment or that investments in this direction are risky. This is in line with the results of the survey: 24 participants (96%) see the low level of digitization of production facilities and 22 participants (88%) the high costs for IT equipment as a

Table 5
Potential barriers of implementing the CMfg model in IC.

Barrier	Description
Poor data quality	The quality of data used in the design process might be too low in order to be processed by the CMfg system. It will be required to input the requirements according to specific data standards and incorporate sufficient details about the product. Planners might not have the knowledge, tools or financial incentive to generate this data.
Shifting of competitive advantages	There might be a risk that services providers shift their competitive advantages (e.g., know-how) to other project stakeholders. If they use special intellectual property for offering their products to customers, they might be reluctant to expose themselves on such a public platform.
Contractual issues with existing legal frameworks	Current project delivery methods in AEC are characterized by bilateral contracts between the owner, architect, contractor, etc. This can be a barrier to scheduling and managing fabrication via a multi-party cloud system.
Less direct interactions of planners and manufacturers	The stakeholders involved including the owner, planners and manufacturers might be unwilling to collaborate via a platform and rather prefer a direct exchange with specific companies and their representatives.
Low digitalization of production facilities	Advanced technical equipment is required to enable the virtualization of manufacturing resources. Today's manufacturing facilities might not have the required level of digitization for enabling automated order processing and real-time monitoring.
High cost for implementing IT equipment	The cost for implementing the required sensing (e.g., scanners) and actuating (e.g., manufacturing bridges) technologies in the production facilities might be too high for individual companies.
High cost for training personnel	It might be too expensive to train employees of planning offices and prefabrication companies to work according to the new workflow.

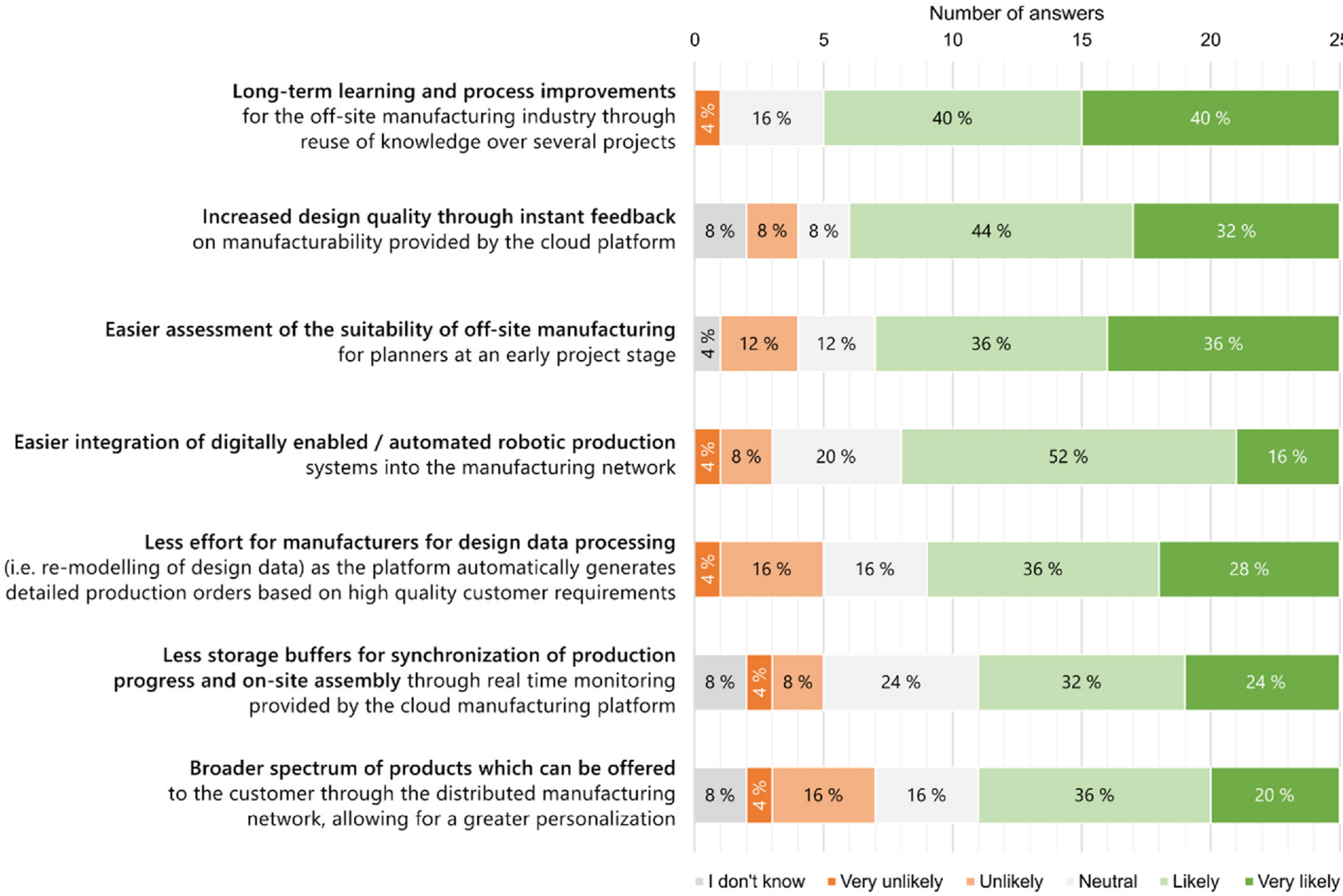

Fig. 11. Assessment of potential benefits of applying CMfg in AEC sector by the participants. Sorted by summarized proportion of "likely" and "very likely". n = 25.

barrier. One respondent comments, that such a platform alone will not automatically make production more digital. Instead, the technologies alone must first prove themselves in terms of better quality and financial advantages. Also, spontaneously adapting the production procedure once it is started would not be any more possible with such a CMfg platform, because the process from ordering materials, manufacturing, quality control to shipping is very lengthy.

5.2. Scenario assessment

The evaluation of the survey participants' responses to the desirability of the scenarios introduced shows that the overwhelming majority considers them to be desirable or very desirable (see Fig. 13). Scenario B receives the greatest desirability among all participants. A possible suggestion of manufacturing services by the CMfg system (scenario C) is the least desired of all scenarios, but still more than half respectively 17 participants (68%) find it desirable or very desirable. Placing orders and monitoring production progress via the CMfg platform (scenario D) is similarly desired as the use of cloud-based software (scenario A).

The interviewees were predominantly positive about the scenarios. Criticism was mainly related to specific details. For scenario A, it was noted that these tools are helpful for real estate developers because they allow them to understand what options they have. In this regard, one respondent noted that the use of software via the cloud is already possible today. Scenario A is therefore most likely to correspond to the current state of practice. In this respect, it would be important how the tools provided would work together and how they could incorporate information from production. In this regard, one interviewee notes that the presentation and processing of more complex data would need to be made simpler.

For scenario B, several respondents expressed great interest in preliminary cost estimates. This would allow developers and investors to obtain information regarding costs and schedules at an early stage. However, one respondent notes that this preliminary estimate would not be usable if feasibility is not assured. He therefore estimates scenario C to be more reasonable. Another interviewee expresses a similar opinion, saying that a more detailed DFMA feedback at an early stage is very important.

For scenario C, several respondents express concerns that such a high LOD model as envisioned is not realistic. Architects would not model such in-depth intricacies to limit their choices. One respondent described the situation as follows: Customers want to have valuable metrics on feasibility, costs, etc. at an early stage of the project using a still flexible LOD 200 model. However, these metrics would require an LOD 400.

For scenario D, one respondent stated that the scenario is attractive, but the most difficult to achieve. For this, all data inconsistencies would have to be resolved beforehand so that this comprehensive monitoring could work. Still, this would be very valuable for the clients because they could measure the performance of the executing company and achieve more transparency, comment several interviewees. In this regard, there are already companies that would enable monitoring of the supply chain.

5.3. Suggestions on future implementations

With regard to the development of a real CMfg system, there is a general opinion among the interviewees that it would be better to work with a smaller selection of AEC companies representing different project roles. The experts indicate that some investors will only want to work with a private network of companies with which they have experience. In doing so, they will want to define the technologies used

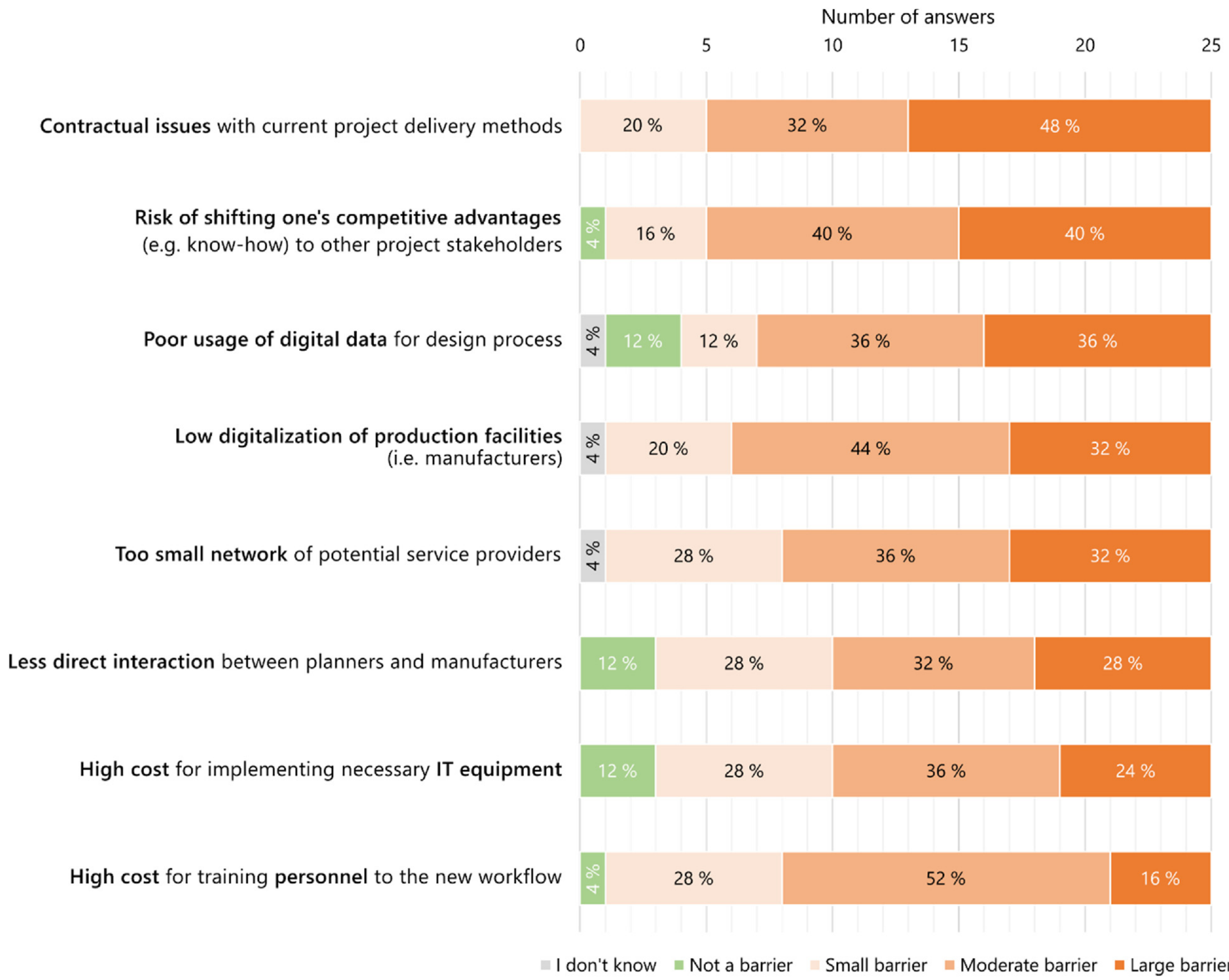

Fig. 12. Assessment of potential barriers during implementation of a CMfg system in the AEC sector by the participants. Sorted by proportion of "large barrier". n = 25.

in the supply chain. A well thought out procedure for implementation was assessed as important. It would make sense to start with systematized products and then move to more complex ones. These initial products could be wall panels, bathroom pods or conference rooms. Therefore, it would be important to once realize the process from uploading a design draft onto the platform, to evaluating and computing estimates, to digitally monitoring manufacturing. Special attention must be placed on the way how such a future platform should handle data. Regarding the necessary accuracy of the models, a LOD 200/250 model seems sufficient, because it contains the minimum necessary data, and all higher detailed models would limit the scope of potential manufacturing options too much.

6. Discussion

6.1. Opportunities of application

The evaluations of the results have highlighted the potential benefits of a CMfg system for IC. Thereby, the results differ slightly between the survey and the interviews. Interestingly, the quantitative analysis of the survey revealed that the most likely benefit is a long-term improvement of IC processes. In addition to this rather general assessment, better quality of designs and easier assessment of the suitability of IC in early phases are also seen as likely benefits. Besides, most respondents find that a CMfg system would make it easier to deploy more advanced manufacturing equipment.

The interview participants were less likely to emphasize a long-term learning as a possible advantage. In contrast, the improvement of the design process was emphasized more strongly. The immediate feedback from the cloud could help to take production-relevant information into account in the early stages of planning. Furthermore, the results show that increased transparency would be an important advantage of the platform. The integration of services in the cloud would be beneficial for project developers to get a good overview of the market and a possible application of IC in a construction project. They could make better, financially sound planning decisions. Finally, benefits for off-site manufacturers in terms of financial aspects were also recognized. The cloud platform can open new sales channels for them and improve machine efficiency through more stable utilization rates. This expected benefit is consistent with previous studies on e-commerce platforms for IC (Raju and Feldman, 2017; He et al., 2018). Thus, according to the interview results, the CMfg model can be considered helpful for coping with poor synchronization between design and manufacturing and risky investments.

6.2. Possible challenges along the way towards realization

The evaluations have revealed many potential organizational and technological barriers to the implementation of such a CMfg platform. Both the quantitative results of the survey and the qualitative results of the interviews indicate that the current contractual framework is a major organizational obstacle. In particular, the interviewees' statements point

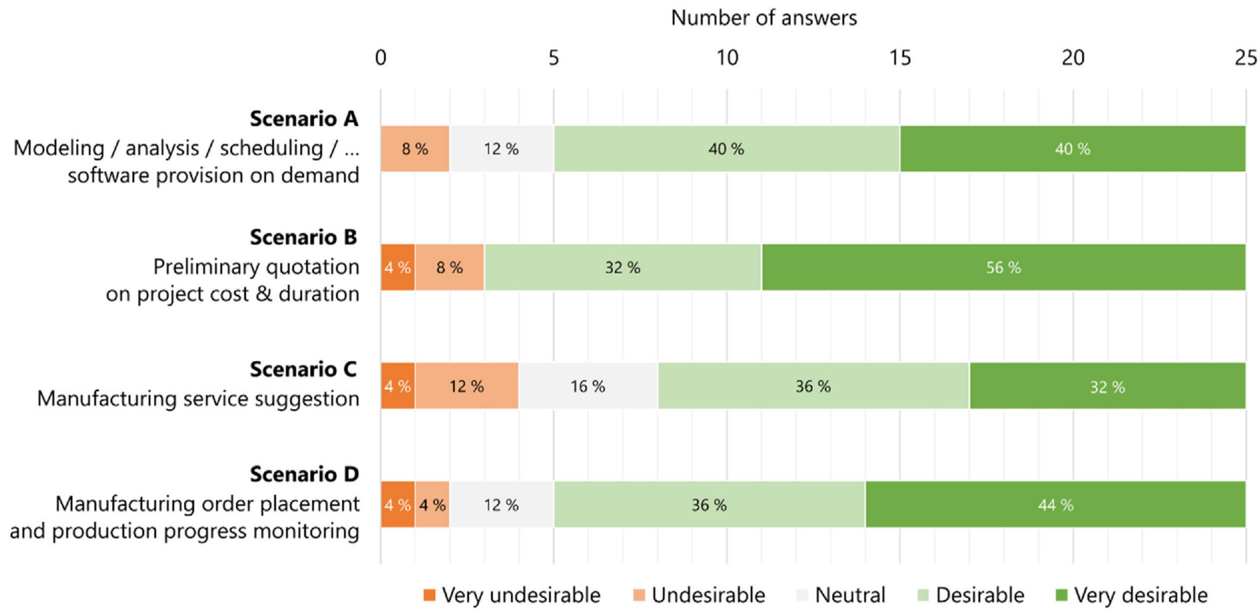

Fig. 13. Desirability of the introduced scenarios. n = 25.

to current specificities of project execution that stand in the way of CMfg. As long as there was no financial incentive, designers would not want to incorporate manufacturing-relevant aspects into their work. At the same time, it would not be desirable for producers to share precise details of their manufacturing processes with a broad mass. For one thing, they would not have the necessary expertise, and for another, this would endanger their current business models. For these reasons, many respondents see the need for closer collaboration between all project participants in order to operate such a platform in a meaningful way (Hall et al., 2020). Still, there is a possibility that candidates may be projecting current problems in construction projects that they know about on the CMfg model.

Finally, the evaluation shows that the form of data generation, storage and processing are significant barriers. Although there is a small proportion of participants in the survey who do not see this as a barrier, a large majority of respondents still perceive it as one. This is even more evident in the results of the interviews. Here, many interviewees point out that the quality of data during planning is not sufficient to perform meaningful analyses for execution. There is a need for much more advanced solutions for linking data in order to integrate the large amount of different information sources (Cao et al., 2021b). In addition, it became clear that the development of intelligent algorithms that would use this data to perform analyses in terms of feasibility and anticipated costs would be a very complex task.

6.3. Scenarios for applying CMfg in IC

The conceptualized scenarios were assessed as predominantly desirable for IC both in the survey and during the interviews. Based on the quantitative results from the survey, scenario B can be identified as the most desirable. According to this, most respondents see the advantages of such a CMfg platform for IC in an accurate preliminary estimation of costs and time. This is consistent with the large body of publications addressing greater integration of planning and manufacturing in IC (Razkenari et al., 2019; Cao et al., 2021a; Qi et al., 2021). The interviewees expressed similar views. Based on their statements, it was also possible to identify detailed concerns regarding a comprehensive manufacturability analysis and service matching as envisioned in scenario C. Here, the requirements for data quality seem to be too high to be achieved in reality. This could be an indication of why this scenario appears to be less desirable among the respondents of the survey.

6.4. Limitations of this research

It is plausible that a few limitations might have influenced the results obtained. Since the focus of this study was on a manufacturing model that is not yet widely adopted in any industry there is a possibility that the respondents' assessments are influenced in a certain way by the explanations provided by the authors. It was tried, however, to explain the model as objective as possible, as well as to point out the few existing examples of applications so that the respondents can draw more independent conclusions. Similarly, the premises that led to the deductive development of the adapted model and scenarios of CMfg for IC might influence the reliability of conclusions.

Due to the small survey size, it was unfortunately not possible to conduct more comprehensive statistical analyses alongside the descriptive analyses carried out herein. However, the use of descriptive statistics is in the opinion of the authors still appropriate for CMfg as a novel and emerging topic. In addition, the questionnaire applied in this study entails the limitation that a proper understanding of the contents explained at the beginning cannot be ensured by the people who did the questionnaire.

Since this study only focuses on investigating how CMfg can be beneficial for IC, it is not clear if there are other more suitable manufacturing models. Further data collection is required to determine exactly to which extent the individual characteristics of CMfg can be more beneficial for solving the identified problems than related research approaches.

6.5. Future work on the CMfg model for IC

Based on this broad investigation, more in-depth research should be initiated in relation to specific organizational and technological challenges identified. A promising solution is to develop a joint prototype of a private CMfg platform with a selection of two to three geographically close, innovative companies per role, as it was done in pilot studies within the manufacturing industry (Ren et al., 2017). These should focus on systematized products such as wall panels, bathroom pods or meeting rooms. As soon as the process from design to execution planning to production with subsequent delivery has been made possible in this context in terms of data technology and organization, it will be easier to implement a large-scale platform grounded on open standards. This could be achieved by combining several private platforms to a hybrid CMfg system.

There is a great need to consider the following aspects in particular on the way to a fully integrated CMfg platform. Firstly, the legal framework would have to be examined in more detail. Here, there is a need to work out the obligations of the participants and the influence of over-regional legislation in more detail. Also, the role of the owner, which has been little illuminated in this model, should be investigated more closely since they bill for individual services. Similarly, the question about the platform operator would need to be addressed. It is possible that financially well-positioned real estate developers could act as operators to better control their supply chain and ensure a return on investment.

Secondly, suitable data structures and interfaces must be developed to enable the exchange of information between planning and manufacturing. For this, solutions from other, more advanced sectors such as web service providers or automotive industries might be helpful. Yet, it is crucial that these technological solutions are very well integrated into the way AEC stakeholders work and that the entry thresholds are kept low, as otherwise the implementation effort will nullify the benefits. In this sense it might be helpful to involve manufacturers to define quantitative measurements required to describe and monitor services. This could serve as a basis for defining the quality of services (QoS) as proposed by Xu (2012).

Thirdly, the financial incentives for individual actors would have to be investigated. If comprehensive knowledge is no longer stored at the off-site manufacturers but in the CMfg system, it would be important to find out how they can continue to make profits and who will continue to expand the knowledge towards more efficient IC.

Finally, the question arises to what extent the implementation of the CMfg model in the AEC sector is comparable to the introduction of other groundbreaking approaches. It could be interesting to investigate whether there are analogies between CMfg and BIM in terms of early adopters, company size, contractual impacts, etc. and whether there is value to be gained from these similarities in the future.

7. Conclusion

This paper has investigated how the novel CMfg model can be useful to foster the application of IC. First an adapted CMfg model for IC was developed including key model characteristics, a process structure alongside four application scenarios. A brainstorming session was performed to additionally elaborate on potential benefits and barriers. To evaluate the opportunities and eventual challenges of a CMfg model for IC two different research methods were applied: On the one hand, an online survey among 25 industry practitioners was conducted to get a quantitative assessment from a broad perspective. On the other hand, through 12 interviews with experts a qualitative assessment of the adapted model was performed.

It can be concluded from the findings that the CMfg model has the chance to achieve several benefits if applied in an IC context. Quantitative and qualitative results indicate that an improvement in design quality regarding manufacturability and an easier assessment of the suitability of IC for project developers are the most important opportunities. Additionally, a CMfg model can be financially advantageous for off-site manufacturers both for the economic operation of machinery and acquiring new orders. Particularly the quantitative results suggest that a CMfg platform is expected to enable process improvements for IC in the long term.

Furthermore, this study was able to elaborate on important challenges on the way to implementing a CMfg platform for the construction industry. The organizational barriers include current contractual conditions. Besides, a fully comprehensive platform would not be compatible with the current business models of manufacturers. Technological barriers identified include inadequate data structures in the design process. In addition, the manufacturing facilities do not seem ready for comprehensive real-time monitoring via such a platform.

The results further suggest that the application of the CMfg model is seen as desirable in various scenarios. Especially, the estimation of costs and production times in early project phases attracts great interest among the respondents.

It is recommended that future research should be conducted with regard to suitable contractual frameworks, adequate data structures, and promising monetarization models for a CMfg platform in the construction industry. To this end, a group of selected companies could be motivated by the highlighted benefits to collaboratively build a working prototype of a CMfg platform.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the survey participants and interview partners for their valuable input and time. Their assessments and rich insights are greatly appreciated.

References

3D HUBS B.V., 2022. 3D Hubs. Retrieved from: https://www.hubs.com/.

Agapiou, A., 2022. Barriers to offsite construction adoption: a quantitative study among housing associations in England. Buildings 12 (3). https://doi.org/10.3390/buildings12030283.

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M.J., et al., 2017. Reinventing Construction: a Route to Higher Productivity. McKinsey Global Institute.

Beelse, 2021. Beelse Cloud Manufacturing. Retrieved from: https://www.beelse.com/en/.

Blismas, N., 2007. Off-site Manufacture in Australia: Current State and Future Directions.

Cao, J., Bucher, D.F., Hall, D.M., Lessing, J., 2021a. Cross-phase product configurator for modular buildings using kit-of-parts. Autom. Constr. 123. https://doi.org/10.1016/j.autcon.2020.103437.

Cao, J., Vakaj, E., Hall, D., 2021b. Ontology-Based Cloud Manufacturing Framework in Industrialized Construction.

Cao, J., Vakaj, E., Soman, R.K., Hall, D.M., 2022. Ontology-based manufacturability analysis automation for industrialized construction. Autom. Constr. 139 (April), 104277. https://doi.org/10.1016/j.autcon.2022.104277.

Chui, M., Mischke, J., 2019. The impact and opportunities of automation in construction. In: McKinsey & Company. Retrieved from: https://www.mckinsey.com/business-functions/operations/our-insights/the-impact-and-opportunities-of-automation-in-construction.

Creswell, J., 2013. Qualitative, Quantitative, and Mixed Methods Approaches, Research Design. Sage Publications.

Fast Radius Inc, 2021a. Cloud Manufacturing. Retrieved from: https://fastradius.com/wp-content/uploads/2021/01/Cloud-Manufacturing-White-Paper.pdf.

Fast Radius Inc, 2021b. FastRadius - Our Factories. Retrieved from: https://www.fastradius.com/our-factories/.

Fictiv Inc, 2022a. Become a partner - Fictiv. Retrieved from: https://www.fictiv.com/become-a-partner.

Fictiv Inc, 2022b. Fictiv: Custom Manufacturing On-Demand from Prototype to Production. Retrieved from: https://www.fictiv.com/.

Fisher, O., Watson, N., Porcu, L., Bacon, D., Rigley, M., Gomes, R.L., 2018. Cloud manufacturing as a sustainable process manufacturing route. J. Manuf. Syst. 47, 53–68. https://doi.org/10.1016/j.jmsy.2018.03.005.

Franke, N., Schreier, M., 2008. Product uniqueness as a driver of customer utility in mass customization. Mark. Lett. 19 (2), 93–107. https://doi.org/10.1007/s11002-007-9029-7.

Gan, X., Chang, R., Zuo, J., Wen, T., Zillante, G., 2018. Barriers to the transition towards off-site construction in China: an interpretive structural modeling approach. J. Clean. Prod. 197, 8–18. https://doi.org/10.1016/j.jclepro.2018.06.184.

Goulding, J., Arif, M., 2013. Offsite Production and Manufacturing - Research Roadmap Report. CIB General Secretariat. Retrieved from: https://site.cibworld.nl/dl/publications/pub_372.pdf.

Grilo, A., Jardim-Goncalves, R., 2011. Challenging electronic procurement in the AEC sector: a BIM-based integrated perspective. Autom. Constr. 20 (2), 107–114. https://doi.org/10.1016/j.autcon.2010.09.008.

Hall, D.M., Whyte, J.K., Lessing, J., 2020. Mirror-breaking strategies to enable digital manufacturing in Silicon Valley construction firms: a comparative case study. Constr. Manag. Econ. 38 (4), 322–339. https://doi.org/10.1080/01446193.2019.1656814.

He, D., Li, Z., Wu, C., Ning, X., 2018. An e-commerce platform for industrialized construction procurement based on BIM and linked data. Sustainability (Switzerland) 10 (8). https://doi.org/10.3390/su10082613.

Hussain, A., 2022. Deloitte 2022 engineering and construction industry outlook. Retrieved from: https://www2.deloitte.com/content/dam/Deloitte/us/Documents/energy-resources/us-2022-outlook-engineering-and-construction.pdf.

Jayasekara, D., Pawar, K., Ratchev, S., 2019. A Framework to Assess Readiness of Firms for Cloud Manufacturing. In: Proceedings - 2019 IEEE International Conference on Engineering, Technology and Innovation, ICE/ITMC 2019. https://doi.org/10.1109/ICE.2019.8792648.

Jensen, K.N., Nielsen, K., Brunoe, T.D., 2018. Mass customization as a productivity enabler in the construction industry. In: Advances in Production Management Systems. Production Management for Data-Driven, Intelligent, Collaborative, and Sustainable Manufacturing. Springer International Publishing, pp. 159–166. https://doi.org/10.1007/978-3-319-99704-9.
Johnson, R.B., Onwuegbuzie, A.J., 2004. Mixed methods research: a research paradigm whose time has come. Educ. Res. 33 (7), 14–26. https://doi.org/10.3102/0013189X033007014.
Kalemi, E.V., Cheung, F., Tawil, A.R., Patlakas, P., Alyania, K., 2020. ifcOWL-DfMA a new ontology for the offsite construction domain. In: CEUR Workshop Proceedings, vol. 2636, pp. 105–117.
Lessing, J., Stehn, L., Ekholm, A., 2005. Industrialised housing: definition and categorization of the concept. In: 13th International Group for Lean Construction Conference: Proceedings, pp. 471–480.
Li, B.H., Zhang, L., Wang, S.L., Tao, F., et al., 2010. Cloud manufacturing: a new service-oriented networked manufacturing model. Jisuanji Jicheng Zhizao Xitong/Comput. Integr. Manuf. Syst., CIMS 16 (1), 1–7.
Li, Z., Wang, W.M., Liu, G., Liu, L., et al., 2018. Toward open manufacturing a cross-enterprises knowledge and services exchange framework based on blockchain and edge computing. Ind. Manag. Data Syst. 118 (1), 303–320. https://doi.org/10.1108/IMDS-04-2017-0142.
Li, X., Shen, G.Q., Wu, P., Yue, T., 2019. Integrating building information modeling and prefabrication housing production. January Autom. Constr. 100, 46–60. https://doi.org/10.1016/j.autcon.2018.12.024.
Li, X., Wu, L., Zhao, R., Lu, W., et al., 2021. Two-layer Adaptive Blockchain-based Supervision model for off-site modular housing production. Comput. Ind. 128, 103437. https://doi.org/10.1016/j.compind.2021.103437.
Li, X., Lu, W., Xue, F., Wu, L., Zhao, R., Lou, J., Xu, J., 2022a. Blockchain-enabled IoT-BIM platform for supply chain management in modular construction. J. Constr. Eng. Manag. 148 (2), 1–18. https://doi.org/10.1061/(asce)co.1943-7862.0002229.
Li, X., Wu, C., Xue, F., Yang, Z., Lou, J., Lu, W., 2022b. Ontology-based mapping approach for automatic work packaging in modular construction. Autom. Constr. 134, 104083.
Lim, M.K., Xiong, W., Lei, Z., 2020. Theory, supporting technology and application analysis of cloud manufacturing: a systematic and comprehensive literature review. Ind. Manag. Data Syst. 120 (8), 1585–1614. https://doi.org/10.1108/IMDS-10-2019-0570.
Lim, M.K., Xiong, W., Wang, Y., 2022. A three-tier programming model for service composition and optimal selection in cloud manufacturing. Comput. Ind. Eng. 167 (January), 108006. https://doi.org/10.1016/j.cie.2022.108006.
Liu, Y., Xu, X., 2017. Industry 4.0 and cloud manufacturing: a comparative analysis. J. Manuf. Sci. Eng. Trans. ASME 139 (3), 1–8. https://doi.org/10.1115/1.4034667.
Liu, Y., Wang, L., Wang, X.V., Xu, X., Jiang, P., 2019a. Cloud manufacturing: key issues and future perspectives. Int. J. Comput. Integr. Manuf. 32 (9), 858–874. https://doi.org/10.1080/0951192X.2019.1639217.
Liu, Y., Wang, L., Wang, X.V., Xu, X., Zhang, L., 2019b. Scheduling in cloud manufacturing: state-of-the-art and research challenges. Int. J. Prod. Res. 57 (15–16), 4854–4879. https://doi.org/10.1080/00207543.2018.1449978.
Mao, C., Shen, Q., Pan, W., Ye, K., 2015. Major barriers to off-site construction: the developer's perspective in China. J. Manag. Eng. 31 (3), 04014043. https://doi.org/10.1061/(asce)me.1943-5479.0000246.
Mourad, M., 2018. Interoperability Assessment in Cloud Manufacturing. University of Bath.
Muñoz-La Rivera, F., Mora-Serrano, J., Valero, I., Oñate, E., 2021. Methodological-technological framework for construction 4.0. Arch. Comput. Methods Eng. 28 (2), 689–711. https://doi.org/10.1007/s11831-020-09455-9.
Pan, W., Gibb, A.G.F., Dainty, A.R.J., 2012. Strategies for integrating the use of off-site production technologies in house building. J. Constr. Eng. Manag. 138 (11), 1331–1340. https://doi.org/10.1061/(asce)co.1943-7862.0000544.
Qi, B., Razkenari, M., Costin, A., Kibert, C., Fu, M., 2021. A systematic review of emerging technologies in industrialized construction. J. Build. Eng. 39, 102265. https://doi.org/10.1016/j.jobe.2021.102265 (October 2020).
Raju, P., Feldman, G., 2017. 2.1 Introduction 2 Exploiting e-commerce in construction. In: Advances in Construction ICT and e-Business, pp. 21–32.
Raju, P., Feldman, G., 2020. 2 Exploiting e-commerce in construction. In: Perera, S., Ingirige, B., Ruikar, K., Obonyo, E. (Eds.), Advances in Construction ICT and e-Business. Routledge, London, England, pp. 21–32.
Rauch, E., Seidenstricker, S., Dallasega, P., Hämmerl, R., 2016. Collaborative cloud manufacturing: design of business model innovations enabled by cyberphysical systems in distributed manufacturing systems. J. Eng. 2016. https://doi.org/10.1155/2016/1308639.
Razkenari, M., Bing, Q., Fenner, A., Hakim, H., Costin, A., Kibert, C.J., 2019. Industrialized construction: emerging methods and technologies. In: Computing in Civil Engineering 2019. American Society of Civil Engineers, Reston, VA, pp. 352–359. https://doi.org/10.1061/9780784482438.045.
Ren, L., Zhang, L., Zhao, C., Chai, X., 2013. Cloud manufacturing platform: operating paradigm, functional requirements, and architecture design. In: ASME 2013 International Manufacturing Science and Engineering Conference Collocated with the 41st North American Manufacturing Research Conference, MSEC 2013, vol. 2, pp. 1–10. https://doi.org/10.1115/MSEC2013-1185.
Ren, L., Zhang, L., Tao, F., Zhao, C., et al., 2015. Cloud manufacturing: from concept to practice. Enterp. Inf. Syst. 9 (2), 186–209. https://doi.org/10.1080/17517575.2013.839055.
Ren, L., Zhang, L., Wang, L., Tao, F., et al., 2017. Cloud manufacturing: key characteristics and applications. Int. J. Comput. Integr. Manuf. 30 (6), 501–515. https://doi.org/10.1080/0951192X.2014.902105.
Sacks, R., Eastman, C., Lee, G., Teicholz, P., 2018. BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers, third ed. John Wiley and Sons, Nashville, TN.
Saldana, J., 2013. The coding manual for qualitative researchers. In: second ed. SAGE Publications, London, UK.
Simeone, A., Caggiano, A., Boun, L., Deng, B., 2019. Intelligent cloud manufacturing platform for efficient resource sharing in smart manufacturing networks. In: Procedia CIRP. Elsevier B.V., pp. 233–238. https://doi.org/10.1016/j.procir.2019.02.056
Singh, R., Gehlot, A., Akram, S.V., Gupta, L.R., et al., 2021. Cloud manufacturing, internet of things-assisted manufacturing and 3D printing technology: reliable tools for sustainable construction. Sustainability (Switzerland) 13 (13). https://doi.org/10.3390/su13137327.
Skoury, L., Amtsberg, F., Yang, X., Wagner, H.J., et al., 2023. A framework for managing data in multi-actor fabrication processes. In: Gengnagel, C. (Ed.), et al., Towards Radical Regeneration. Springer International Publishing, Cham, pp. 601–615.
Tao, F., Zhang, L., Venkatesh, V.C., Luo, Y., Cheng, Y., 2011. Cloud manufacturing: a computing and service-oriented manufacturing model. Proc. Inst. Mech. Eng. B J. Eng. Manuf. 225 (10), 1969–1976. https://doi.org/10.1177/0954405411405575.
VERBI GmbH, 2022. MAXQDA Software for Qualitative and Mixed Methods Data Analysis. Retrieved from: https://www.maxqda.com/.
Vincent Wang, X., Xu, X.W., 2013. An interoperable solution for Cloud manufacturing. Robot. Comput. Integr. Manuf. 29 (4), 232–247. https://doi.org/10.1016/j.rcim.2013.01.005.
Wang, X.V., Xu, X., 2014. Cloud manufacturing in support of sustainability. In: ASME 2014 International Manufacturing Science and Engineering Conference, MSEC 2014 Collocated with the JSME 2014 International Conference on Materials and Processing and the 42nd North American Manufacturing Research Conference, vol. 1, pp. 1–9. https://doi.org/10.1115/MSEC2014-4020.
Wei, J., Liu, Y., Wang, L., Sun, X., 2021. Research on evaluation of manufacturing cloud service oriented to environmental benefits of supply chain. Environ. Sci. Pollut. Res. Int. 28 (42), 59473–59485. https://doi.org/10.1007/s11356-021-13427-2.
Werbrouck, J., Senthilvel, M., Rasmussen, M.H., 2022. Federated data storage for the AEC industry, in: Buildings and Semantics. In: CRC Press, London, pp. 139–164. https://doi.org/10.1201/9781003204381-8.
Wu, D., Rosen, D.W., Schaefer, D., 2014. Cloud-Based Design and Manufacturing: Status and Promise. In: Schaefer, D. (Ed.), Cloud-Based Design and Manufacturing (CBDM): A Service-Oriented Product Development Paradigm for the 21st Century. Springer, Cham, pp. 1–24. https://doi.org/10.1007/978-3-319-07398-9.
Wu, D., Rosen, D.W., Wang, L., Schaefer, D., 2014. Cloud-based manufacturing: old wine in new bottles? Procedia CIRP 17, 94–99. https://doi.org/10.1016/j.procir.2014.01.035.
Wu, D., Rosen, D.W., Wang, L., Schaefer, D., 2015. Cloud-based design and manufacturing: a new paradigm in digital manufacturing and design innovation. Comput. Aided Des. 59, 1–14. https://doi.org/10.1016/j.cad.2014.07.006.
Wuni, I.Y., Shen, G.Q., 2020. Barriers to the adoption of modular integrated construction: systematic review and meta-analysis, integrated conceptual framework, and strategies. J. Clean. Prod. 249, 119347. https://doi.org/10.1016/j.jclepro.2019.119347.
Xometry Inc, 2022a. Xometry - Become a Supplier. Retrieved from: https://www.xometry.com/become-a-supplier/.
Xometry Inc, 2022b. Xometry - Manufacturing on Demand. Retrieved from: https://www.xometry.com/.
Xu, X., 2012. From cloud computing to cloud manufacturing. Robot. Comput. Integr. Manuf. 28 (1), 75–86. https://doi.org/10.1016/j.rcim.2011.07.002.
Yadekar, Y., Shehab, E., Mehnen, J., 2016. Taxonomy and uncertainties of cloud manufacturing. Int. J. Agile Syst. Manag. 9 (1), 48–66. https://doi.org/10.1504/IJASM.2016.076577.
Yang, C., Lan, S., Shen, W., Huang, G.Q., Wang, X., Lin, T., 2017. Towards product customization and personalization in IoT-enabled cloud manufacturing. Cluster Comput. 20 (2), 1717–1730. https://doi.org/10.1007/s10586-017-0767-x.
Zhang, L., Luo, Y., Tao, F., Li, B.H., Ren, L., Zhang, X., Guo, H., Cheng, Y., Hu, A., Liu, Y., 2014a. Cloud manufacturing: a new manufacturing paradigm. Enterp. Inf. Syst. 8 (2), 167–187. https://doi.org/10.1080/17517575.2012.683812.
Zhang, L., Mai, J., Tao, F., Luo, Y., Ren, L., 2014b. Development status of cloud manufacturing in China. In: ASME 2014 International Manufacturing Science and Engineering Conference, MSEC 2014 Collocated with the JSME 2014 International Conference on Materials and Processing and the 42nd North American Manufacturing Research Conference, vol. 1, pp. 1–8. https://doi.org/10.1115/MSEC2014-4019.
Zhang, W., Lee, M.W., Jaillon, L., Poon, C.S., 2018. The hindrance to using prefabrication in Hong Kong's building industry. J. Clean. Prod. 204, 70–81. https://doi.org/10.1016/j.jclepro.2018.08.190.
Zhong, R.Y., Peng, Y., Xue, F., Fang, J., Zou, W., Luo, H., Thomas Ng, S., Lu, W., Shen, G.Q.P., Huang, G.Q., 2017. Prefabricated construction enabled by the Internet-of-Things. Autom. Constr. 76, 59–70. https://doi.org/10.1016/j.autcon.2017.01.006.