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Identifying enablers and relational ontology networks in design for digital fabrication

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A B S T R A C T

As use of digital fabrication increases in architecture, engineering and construction, the industry seeks appropriate management and processes to enable the adoption during the design/planning phase. Many enablers have been identified across various studies; however, a comprehensive synthesis defining the enablers of design for digital fabrication does not yet exist. This work conducts a systematic literature review of 59 journal articles published in the past decade and identifies 140 enablers under eight categories: actors, resources, conditions, attributes, processes, artefacts, values and risks. The enablers' frequency network is illustrated using an adjacency matrix. Through the lens of actor-network theory, the work creates a relational ontology to demonstrate the linkages between different enablers. Three examples are presented using onion diagrams: circular construction focus, business model focus and digital twin in industrialisation focus. Finally, this work discusses the intersection of relational ontology with process modelling to design future digital fabrication work routines.

1. Introduction

1.1. Problem statement

Conventional construction in the architectural, engineering and construction industry suffers from low innovation, low productivity and low capital returns, as well as the tremendous consumption of raw materials and energy in processes and building products [1]. The industry has the opportunity to adopt automation and emerging technologies in order to foster sustainable development for the economy, environment and society [2]. For example, Bock (2015) [3] uses an overlay of S-curves [4] to illustrate the potential future increase in performance of construction automation to address the stagnation and technical limits of conventional construction.

One emerging construction automation is digital fabrication, which refers to data-driven production based on digital design information. In recent research and projects in practice, digital fabrication adoption has been slowly acknowledged and accepted in the built environment. Many suggest that digital fabrication is ready to go beyond its seed phase and enter into a growth phase to see large scale adoption such as has occurred with volumetric modular construction or other forms of industrialised construction. Once deployed at a large scale, digital fabrication can provide these potential automation benefits to the built environment [5]. However, research finds that the diffusion of digital fabrication is strongly linked to the value chains in the design or planning phase [6]. To enable greater adoption, a comprehensive understanding and identification of the *enablers* in *design* for *digital fabrication* is needed. These, however, have not yet been studied in research.

1.2. Research approach and structure of this work

To identify the enablers of design for digital fabrication, the authors of this work conducted a five-stage systemic literature review [7]. The review includes 59 journal articles relevant to design for digital fabrication published from 2011 to mid-2021. The identified enablers are organised into eight categories - actor, resource, condition, attribute, process, artefact, value and risk. The authors attempted to report the identified enablers using terminology that is commonly used and easy to understand by practitioners. For each enabler, a full list of the cited literature is presented in this work, followed by examples of citations

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from literature to explain how the enabler is relevant to digital fabrication adoption. Furthermore, the authors conducted a frequency analysis to investigate how frequently each enabler has been mentioned with one another. The results are presented as a frequency network in an adjacency matrix.

Building upon the findings of the systematic literature review, this work examines relational ontology networks with the enablers through the lens of actor-network theory. To illustrate how the relational ontology networks can work, we develop three example networks with the following foci: (1) circular construction; (2) business model; and (3) digital twin in industrialisation. Each network is mapped using an onion network diagram with the enablers and the frequency weights based on the findings from the systematic literature review. They demonstrate the concepts of design for digital fabrication to address material consumption, improve capital returns and enhance productivity with emerging technology respectively. Furthermore, to assist construction management in operation and practice, this work demonstrates a seven-step methodology to derive a process model from the basis of a systematic literature review and a relational ontology network. To exemplify this, an example process modelling of design for digital fabrication is shown spanning from the concept stage to the execution stage. This work concludes with limitations and potential future research topics to further extend this line of research about design for digital fabrication and network studies.

The findings of this work are threefold. Firstly, the authors identify the enablers of successful design for digital fabrication across multiple categorisations. Secondly, we explicitly draw the link between the enablers and the successful results of digital fabrication adoption using a relational ontology network. Thirdly, this work explores the future workflow of process modelling for management, so as to connect research to practice and assist the adoption by the increasing number of industry practitioners and researchers who are designing for digital fabrication.

2. Point of departure

2.1. Design approaches to digital fabrication

Construction automation has been proposed as a solution to existing industry problems of low innovation, low productivity, low capital returns and poor sustainability performance. The technologies and processes of construction automation include robotic approaches and service robot systems adopted for construction processes. Construction automation can be "considered as a rather complex type of innovation or change" and to fully unfold its potential requires that we "change the whole course and idea of construction in a fundamental way" [3].

Digital fabrication is a key emerging technology for construction automation. Digital fabrication refers to data-driven production [8]. Digital fabrication technologies include both subtractive manufacturing such as Computer Numerical Control (CNC), additive manufacturing such as 3D printing, and robotic assembly of components [9–11]. It is believed that digital fabrication can "outperform the conventional construction over time" [3]. However, the diffusion of digital fabrication involves complex systemic changes across many different actors, resources, processes, and other aspects of the construction industry supply chain. It takes time to enable such changes for the adoption of digital fabrication. Thus, the complex types of innovation or changes for digital fabrication "allow it a pertinent developmental depth and breadth in order for it to fully unfold its potential" [3].

Moreover, digital fabrication requires re-thinking of the design process in practice. The design information required for digital fabrication differs from the information required for conventional construction, where human interpretation of the design drawings and their skills significantly determine the fabrication process and outcomes [3,12]. Instead, digital fabrication is a data-driven production where the predetermined digital thread provides continuity between programming codes and automated machinery. This digital design information must be derived during the design process [6,8].

Recent research reveals that appropriate design management for digital fabrication is needed to assist industry practitioners and researchers to ensure project values can be achieved through digital fabrication adoption [12]. In this work, *design for digital fabrication* refers to a design management approach used to achieve successful digital fabrication adoption. Design for digital fabrication requires a combination of new approaches, outcomes, organisation, management and systems across the value chain during design development. To combine the value chain, firms and projects are exploring new strategies. Linner and Bock [13] and Hall et al. (2020) [14] present that firm-level of vertical integration in design, construction and operations can adopt and manage digital fabrication adoption at a greater scale. Ng et al. (2021) [15] presents that project-level of integration in process, information and organisation can adopt and manage digital fabrication in design in current practice to deliver bespoke design more effectively.

Within the design stage, several studies have used novel design approaches to adopt digital fabrication. Three foundational works should be noted. Bock's (1989) [16] and Bock and Linner's (2012) [5]*Robot-Oriented Design (ROD)* considers "co-adaptation of construction products, processes, organisation and management, and automated or robotic technology, so that the use of such technology becomes applicable, simpler, and/or more efficient" [5]. It also considers life-cycle innovation and technology management in construction in the built environment [3]. Bridgewater's (1993) [17]*Design for Automation (DfA)* embraces rationalisation of design kit-of-parts, design for constructability and machine-friendly systems and the principles of Design for Manufacture and Assembly (DfMA) to minimise numbers of different parts and steps in manufacture and assembly and to maximise the benefits of manufacture technology in construction [17].

More recently, there has been a rise in research on digital fabrication with an explicit focus on design and design management. For example, Ng et al. (2020) [6] and Ng et al. (2021) [15]*Design for Digital Fabrication (DfDFAB)* considers DfMA principles to facilitate post-rationalisation, modularisation and mass customisation for digital fabrication adoption [18]. They also consider how Building Information Modelling (BIM) based digital systems enable project management for DfDFAB [6]. Additional past scholarship such as Pan et al. (2018) investigates enabling digital fabrication through management for sustainability in the early planning phase; Linner et al. (2020) [19] studies technology management systems for single-task construction robots from planning to implementation through the concept of Plan-Do-Check-Act.

However, to the authors' knowledge, no research has systematically explored the principles and processes in design for digital fabrication in current practice, including strategies to adopt digital fabrication to address the industry requirements, cost optimisation through innovative value engineering approach and liability requirements in design for digital fabrication. Further, recent research such as Chen et al. (2018) [20] and Pan et al. (2020) [21] study influencing factors for construction automation, in particular, during the implementation phase. There is little research that presents a consistent overview of enablers in design for digital fabrication.

2.2. Enabler research for innovation adoption

Past research has investigated enablers and their interactions in networks to foster industry-wide disruptive changes for digitalisation and innovation adoption. An *enabler* is defined as a way or a medium, which has the capability to provide human or non–human competence to achieve a purpose [22,20]. This term shares a very similar meaning with the terms "mechanism", "practice", "driver", "success factor" or "influencing factor" by many researchers such as Hall et al. (2018) [23], Ruhlandt et al. (2020) [24], O'Connor et al. (2014) [25] and Pan et al. (2020) [21]. In this work, an enabler in design for digital fabrication is understood as a way or a medium, which has the capability to provide project stakeholders or another enabler the required competence to successfully complete the design requirements connected to a digital fabrication process.

From a review of the body of enabler literature, specific to innovation and technology adoption in construction, we identify eight common higher-level categorisations of enablers. Enablers are often presented under eight categories - actor, resource, condition, attribute, process, artefact, value and risk. For example,

Faisal (2010) [22] studies enablers with high strategic importance for effective implementation of sustainability in the design of a supply chain. The identified enablers include information sharing (process), collaborative relationship (attribute), metrics to quantify sustainability benefits in a supply chain (artefact) and availability of funds (condition) Wandahl et al. (2014) [26] explores enablers in open innovation processes in a network through case studies in the construction material industry. The scopes of innovation were categorised into product (artefact), process, organisation (actor), market and technology (resource) and condition. Ozorhon et al. (2014) [27] investigates enablers and barriers to innovation adoption in processes through case studies. The identified enablers include integration (attribute) and leadership (resource) in organisations (actor). The research also identifies that lean construction processes can help to reduce construction waste, project duration and costs (values). Hall et al. (2018) [23] identifies nine specific supply chain integration practices as enablers that foster the adoption of systemic innovation through case studies. The practices include engagement and participation of project owners and key participants such as contractors (actors), multiparty and incentivised contracts (conditions), fiscal transparency (attribute), BIM coordination process and Target Value Design process. They can help to enable fiscal security (values) and reduce wastes (risks) in construction projects. Chen et al. (2020) [20] identifies enablers in the categories of contractual enablers, procedural enablers and technological enablers for supply chain integration through a systematic literature review. The identified enablers include relational contracts (conditions), incentive models (attributes), linked databases for design coordination (artefact), DfMA software platforms and progress monitoring technologies (resources). Specific to construction robotics, Pan et al. (2020) [21] explores 25 influencing factors of using construction robots through a survey. Amongst all, eleven influencing factors such as governmental support (condition) and the prefabrication process were identified as the most critical factors.

Overall, a review of enablers in construction research identifies two key points. Firstly, despite much research on enablers for other types of innovations, enablers for digital fabrication adoption explicitly in the design or planning phase have not yet been studied. Secondly, a study of enablers for new technology in construction cannot be purely technical in nature but requires research and understanding of how enablers are related to a larger socio-technical transition as an innovation diffuses across a network of actors.

2.3. Actor-network theory for innovation and technology studies

Latour (1987) [28] first proposed actor-network theory, which describes the performance and outcomes of a certain reality is a result of how human actants as *actors* and non–human actants interact in heterogenous networks. The theory emphasises the continual transformation and re-configuration of actants towards innovations through their interactions within a network [29]. Hence, an actor-network can be seen as a *relational ontology network*. Latour (2005) [30] sees a network as a method to understand the dynamic ways where relationships between actants are forged, negotiated and maintained.

Moreover, recent construction research has adopted actor-network theory to study collaboration as an actor-network and collective activities as interactions amongst the actants within that network. Harty (2008) [31] explores the implementation of new design and coordination technologies using actor-network theory through interviews and studies of three cases. The results find that delegation of interests on to technological artefacts; and the mobilisation of actors and artefacts can help to limit the scope of negotiations over new technology implementation, to innovate and foster values, as well as to smooth over competing concerns as risks in practice. Adam et al. (2014) [32] uses actor-network theory to explore knowledge sharing (value) in a large Scandinavian architectural firm using an interpretive case study strategy with twelve interviews. Rydin (2013) [33] maps the network of actants with their weights by betweenness through documents analysis, a site visit and interviews with three firms. The findings emphasises the role of material actants connected within the network in the case of regulating low-carbon commercial development in London, United Kingdom. The actants include project managers, policy planners and specialist glass consultants (actors), energy-generating technology (resource) and power flows (artefacts). London and Pablo (2017) [34] examines collaboration as an actor-network using five case studies of innovative housing construction projects. The research identifies nine collaborative practices in actor-network concepts. These practices include shared space condition, shared goals and openness to change in organisations (attribute), mutual problem solving (process) and coherent and explicit standards provision (resources). The research references in the literature adopting actor-network theory mostly conducted case studies. In this work, the authors conducted a systematic literature review to analyse the cases in past scholarship through the lens of actor-network theory.

Based on the above literature, actor-network theory can be especially useful for digital fabrication research because it helps to explain collaborations between human and non–human *enablers* as complex network systems. With such an approach, one can then analyse the emergent relational ontology among the actants in the process from digital design to digital fabrication, based on the weighted relationships between actants. However, to the authors' knowledge, no research has explored the adoption of novel construction automation in construction using actor-network theory. Also, no research has elaborated on network studies in technology management in the design/planning phase for the construction industry.

2.4. Summary of departure

To summarise, this work is developed based on three conceptual pillars: design approaches to digital fabrication, construction innovation enablers, and actor-network theory for innovation and technology studies in construction. From digital fabrication literature, there is only a partial understanding of the design approaches that can be used for digital fabrication; a systematic review of this emergent work does not yet exist. In construction innovation literature, there are many enabler studies which can be categorised into *actor*, *resource*, *condition*, *attribute*, *process*, *artefact*, *value* and *risk*. It should be noted that this categorisation merely serves as one way to organise enablers in research but does not exclude other possible ways to organise enablers exist. These enabler studies indicate that a socio-technical approach is necessary to understand innovations. This socio-technical approach can consider actors, non-actors, and their relationships in an emergent innovation network. Finally, actor-network theory has been used in some cases to explain construction innovation, but no scholarship covers design for digital fabrication through the lens of this theory to the authors' knowledge.

3. Methodology

3.1. Systematic literature review

The research design of this work follows a standard systematic literature review approach, which collects relevant knowledge created in a dedicated research domain, with the aim to extend and/or synthesise that knowledge [35]. Specifically, the authors used the five-stage grounded theory method from Wolfswinkel et al. (2013) [7]. The five stages are *define*, *search*, *select*, *analyse*, and *present*. Fig. 1 summarises

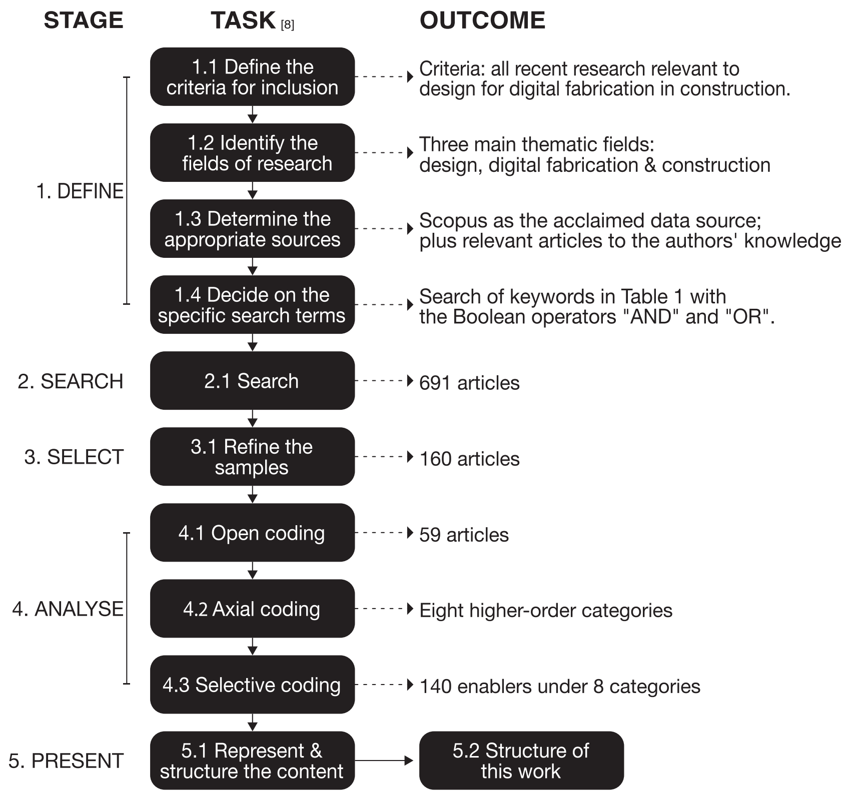


Fig. 1. Research strategy in five systematic literature review stages.

the research steps in this work.

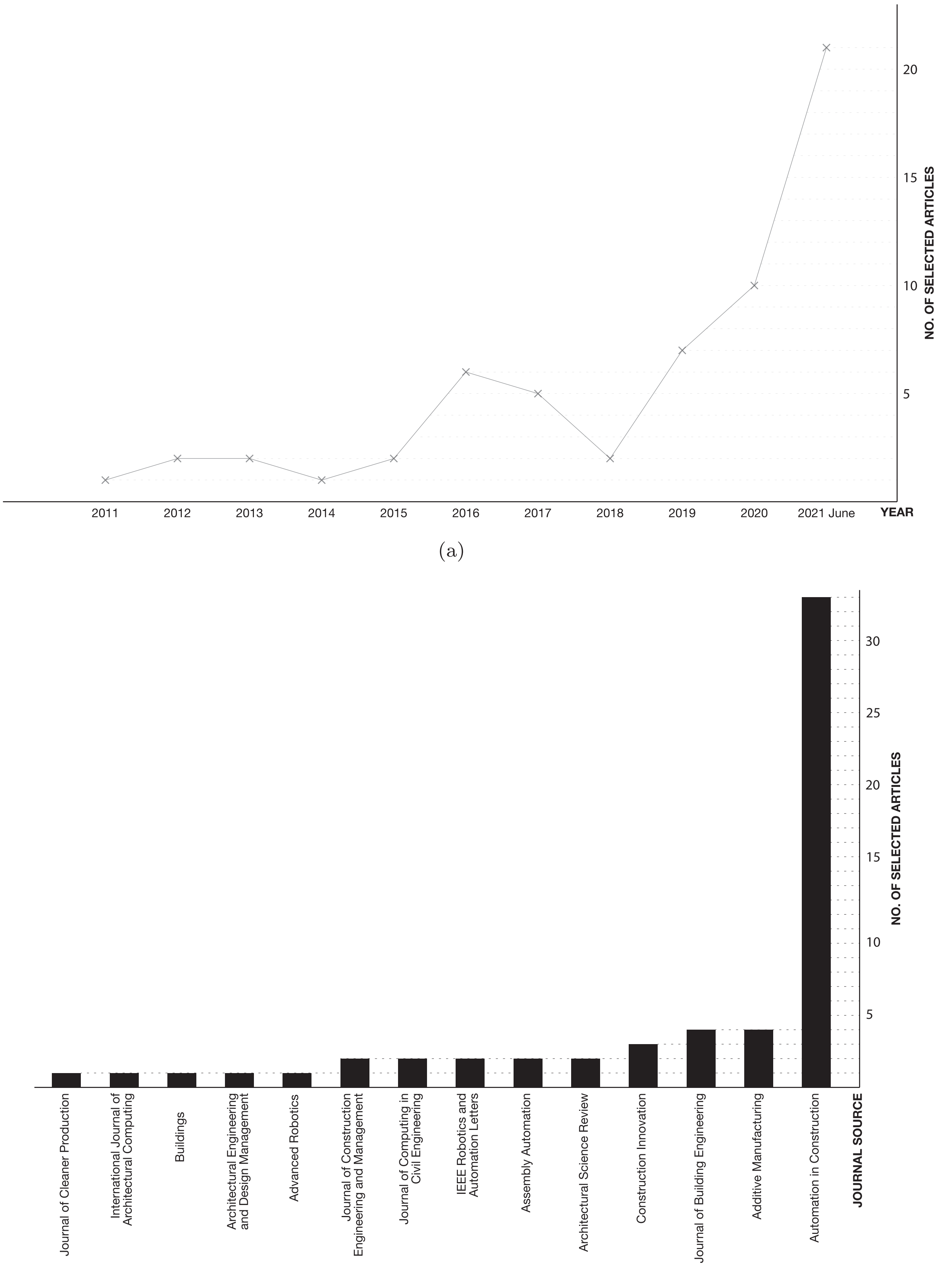
The targeted articles for review are those published within the past ten years from 2011 to mid-2021 (up to the date of data collection in June 2021). The selected period is thereby chosen not only to cover the most recent publications but also due to the higher number of accessible articles in the field. It is important to mention that research in the field was already deducted in earlier periods, especially in Japan in the late 80s to 90s. Unfortunately, that was neither appropriately documented nor published online for researchers to access the relevant articles easily today. At the beginning of the review, the first author of this work firstly used Scopus to search for relevant journal articles, whose titles, abstracts and keywords contain the following terms as shown in Table 1. To ensure quality and narrow the search, the selection was limited to English articles published in high impact journals under the subject areas of engineering, management, computer science, social sciences, material science, arts and humanities, environmental science, mathematics, energy and multidisciplinary studies. This keyword search provided 691 articles as the direct result. The first author read through the abstracts of all the articles to filter irrelevant articles to further condense the literature samples from 691 to 160 articles.

Since design development for digital fabrication has not yet been widely studied, the authors selected the articles based on if their contents involve *design* or *planning* for digital fabrication adoption. Thus, the selection includes not only those research articles studying the design processes for digital fabrication, but also studies exploring strategies to plan for adopting adopt digital fabrication in construction. *Strategy* in this work refers to a long-range plan for actions to bring digital fabrication adoption to success in the design process. The authors excluded articles that merely talk about the technical or technological executions of digital fabrication with neither design nor planning for digital fabrication adoption. *Design/planning* is defined as the value chain as approach, outcome, organisation, management and system of deciding how the digital fabrication technology is being used to deliver the target values of fabrication in a circumstance.

During open coding, the first author read each of the 160 articles in detail. The first author preliminarily conducted a round of open coding to identify proposed enablers found in the data. At this stage, articles with content that did not pertain to the design stage or were overly technical in nature, without consideration of design enablers, were excluded. At the end of the open-coding process, the first author finalised a list of 59 articles for the systematic literature review. Through further axial coding, the first author identified eight higher-order categories as the patterns of the contents in the selected articles and drew the interrelations between the findings in these categories. The first author then re-conceptualised and undertook the selective coding process through a comparative analysis of the findings within and amongst these categories to identify 140 enablers under eight categories. In each of the above steps, the second author also conducted samples of independent analysis and coding and engaged in the feedback on the codes, to ensure reliability. The findings are presented through a qualitative and comprehensive content analysis and data mapping at Stage 5. Fig. 2a presents the numbers of selected articles published per year. Fig. 2b presents the number of selected articles published in the journal sources. Amongst all, 35% of the articles were published in the first half of the year in 2021. Also, 56% of them were published in the journal *Automation in Construction*.

Table 1
Keywords used for the keyword search in this work.

Design		Digital fabrication		Construction
"design"	AND	"digital fabrication"	AND	"construction"
OR		OR		OR
"design management"		"dfab"		"architecture"
OR		OR		OR
"planning"		"robotics"		"buildings"
OR		OR		OR
"Df"		"automation"		"house"



(b)

Fig. 2. Number of selected articles (a) per year, (b) from each journal source.

3.2. Frequency analysis and networks mapping

Based on the literature review, the first author of this work further conducted a frequency analysis to investigate the *frequency weight*, which is defined how often one enabler is mentioned together with another enabler in terms of the number of articles. For example, amongst all 59 articles selected, when two articles mentioned both enabler X and enabler Y in the contents, the frequency weight between X and Y is two. The results of the analysis are presented as a frequency network in an adjacency matrix with heat map visualisation to indicate the frequency weight between any two enablers. Heat map visualisation was chosen because it displays graphically and represents each weight by a colour scale using a hierarchical cluster structure for clear visualisation of the data [36].

Furthermore, the first author then demonstrated the studies of relational ontology networks of the enablers through the lens of actor-

Table 2
Overview of the background information of the selected articles. Research method types: Type A - Prototype/proof of concept development; Type B - System engineering development/V-Model; Type C - 1:1 Physical mockup for case study validation with realistic materials; Type D - Comparative case study; Type E - Case study based on real-world project(s)/scenario; Type F - Design Science Research/comparison without the system; Type G - Qualitative survey: interview/questionnaire; Type H - Theoretical grounding/framework/workflow; Type J - Key Performance Indicators (KPIs)/indicators/statistical analysis; Type K- Analytical computational simulation. *Abbreviation:*digital fabrication (DFAB): prefabrication (prefab.).

Year	Author	Key concept summary	Ref.	Method type	Arch design	Demonstrator	Real-world
2011	Seo et al.	Automated excavation Task Planner	[37]	A			
2012	Linner et al.	Japan prefab. industrialisation and service	[13]	E			✓
2012	Tibbits & Cheung	Programmable materials for assembly	[38]	A,H			
2013	Jung et al.	Robotic steel beam assembly	[39]	A,C,D			
2013	Martinez et al.	Flexible field factory	[40]	A,C,D,G		✓	
2014	King et al.	Robotic tile placement	[41]	A,E,G	✓	✓	
2015	Bock	Review of construction automation & ROD	[3]	E			✓
2015	Linner et al.	LISA assistive micro-rooms for elderly care	[42]	A,E,G		✓	
2016	Willmann et al.	Robotic timber additive fabrication	[43]	A,C,E	✓	✓	✓
2016	Gattas & You	Folded sandwich cardboard	[44]	A			
2016	Issac et al.	Graph method for optimisation of LISA	[45]	A,C,K			
2016	Lim et al.	CLFDM fused deposition modelling	[46]	A,C,D	✓		
2016	Sweet	Robotic pedagogical framework	[47]	K			
2016	Datta et al.	Scaled prototyping comparison	[48]	A,D			
2017	Block et al.	NEST HiLo lightweight concrete roof	[49]	A,C	✓	✓	
2017	Craveiro et al.	Resource-efficient fabrication software	[50]	A			
2017	Wieckowski	JA-WA mobile robots for walls	[51]	A			
2017	Kasperzyk et al.	Re-prefabrication system using robotics	[52]	A			
2017	Tepavcevic et al.	Thin-shell structure	[53]	A	✓		
2018	Lublasser et al.	Robotic for foam concrete for bare wall	[54]	A,C,F			
2018	Pan et al.	Assessing robotics for sustainability	[55]	B,H,J			
2019	Lundeen et al.	GRCSM Autonomous motion planning	[56]	A,C			
2019	Nabooni et al.	Trabeculae Pavilion: Multi-scale AM	[57]	A,C,E	✓	✓	
2019	Al-Qaryouti et al.	Press-fit folded timber sandwich	[58]	A,C,D	✓		
2019	Veliz et al.	Computing craft-driven robotics for cob	[59]	A,C,G,H			
2019	Mostafavi et al.	Design to robotics of multi-materiality	[60]	A,C,D	✓		
2019	Mechtcherine et al.	CONPrint3D: on-site, monolithic	[61]	A			
2019	Tetik et al.	DDM: direct value-adding and reusability	[62]	D,E,F,G	✓		✓
2020	Abou Yassin et al.	Agent-based modelling for robotic 3D printer	[9]	K			
2020	Linner et al.	STCR-technology management system	[19]	B,E			
2020	Kontovourkis & Tryfonos	Clay robotics additive manufacturing	[63]	A,C	✓		
2020	Al-Saeed et al.	Automation using BIM digital objects	[64]	A,C,H			
2020	Craveiro et al.	Additive manufacturing graded concrete	[65]	A,C			
2020	Pan et al.	Factors for using robotics in Hong Kong	[21]	G,H,J			
2020	Hack et al.	Mesh Mould on-site stay-in-place formwork	[66]	A,C,E	✓	✓	
2020	Aagaard & Larsen	Timber fabrication workflow for sawlogs	[67]	A,C			
2020	Zhou et al.	Planetary LEGO Brick for lunar in situ	[68]	A,C	✓		
2020	Laghi et al.	3D-printed stainless steel diagrid column	[69]	A,C,E	✓	✓	
2021	Ali et al.	Robot-based facade spatial assembly	[70]	A	✓		
2021	Apolinarska et al.	Timber assembly reinforced learning algorithm	[11]	A,C			
2021	Asadi et al.	Vision-based mobile robotic for manipulation	[71]	A,C			
2021	Brosque et al.	Manual & robotic concrete drilling	[72]	D,E,G			✓
2021	Brutting et al.	Reusable structural kits-of-parts	[73]	A,H	✓		
2021	Chai et al.	Robotic band saw cutting technique for glulam	[74]	A,C,H	✓		
2021	Gomaa et al.	3D printing for earth-based cob	[75]	A			
2021	Hayashi & Gondo	Reinforced-concrete free-form roof formwork	[10]	A,D,E,G	✓		
2021	Hu et al.	Cost-benefit analysis of cable-driven robot	[76]	A,C,D,E,H,J			
2021	Kim et al.	BIM-IFC robotic painting	[77]	A			
2021	Kunic et al.	Robotic reversible timber battens	[78]	A,C	✓	✓	
2021	Liu et al.	Brainwave-driven human-robot collaboration	[79]	A,C			
2021	Liu et al.	BIM-BVBS with openBIM for steel prefab.	[80]	A,H	✓		
2021	McAlorum et al.	Robotic spray coating on concrete	[81]	A,C			
2021	Nagatani	Open design for infrastructure	[82]	A			
2021	Ng et al.	DfDFAB comparative case study	[15]	D,E,H	✓	✓	✓
2021	Pradhananga et al.	US DFAB adoption barriers	[83]	E,G			
2021	Wagner et al.	Inchworm robots & smart blocks	[84]	A			
2021	Weng et al.	BIM to lattice toolpath planning in 3D Printing	[85]	A,D			
2021	Wermelinger et al.	Stone grasping and object reorientation	[86]	A,C			
2021	Yabanigul & Yazar	Gyroid-like modular robotic hotwire cutting	[87]	A,H	✓		

network theory [28,29]. In this work, three examples of the networks focusing on circular construction, business model and digital twin in industrialisation respectively are demonstrated. The network studies aim to investigate what enablers can enable a specified focus in design for digital fabrication. Each network is illustrated in an onion diagram, where the core is composed of the focal enabler(s) that specifies a certain focus. The number of *onion layers* is the number of articles that mention all the focal enabler(s). Each enabler with its frequency weight of one or above with the focal enabler(s) is mapped as a node on the layer accordingly to the rule that those with a higher frequency weight locate on an inner layer. The nodes are coloured according to their categories. Also, the higher its frequency weight with the focal enabler(s), the bigger the diameter of the node. The frequency weight between any two enablers in the diagram is also reflected in the line weight of the edge in between. An onion diagram illustration was chosen over a force-directed diagram because an onion diagram helps to emphasise the frequency weight of an enabler with the focal enabler, which is the primary message the relational ontology study delivers in this work. It also helps to eliminate the clustering force due to either the source articles or the categories. The distance between two onion layers is laid out for clearer visualisation. It does not represent the network values.

4. Reference clustering

The first author clustered the references with all 59 articles selected, following Watson and Webster (2020) [35]. The article's background information is summarised in Table 2. Reference clustering provides a thought-provoking insight for a better understanding of the contents and methods of the studies in the articles selected in this work. Amongst all, 34% of the selected articles describe the architectural design processes of digital fabrication; 17% of them describe digital fabrication in demonstrator projects; while only 10% of them describe digital fabrication in real-world projects (a.k.a. commercial projects). Regarding research methods of the literature, 81% of the selected articles study digital fabrication with Type A - Prototype/proof of concept development;46% of them use Type C - 1:1 Physical mockup for case study validation with realistic materials; 25% use Type E - Case study based on real-world project(s)/scenario; 22% use Type H - Theoretical grounding/framework/workflow and 20% use Type D - Comparative case study.

5. Identified enablers

The number of enablers in each category and the definitions are presented in Table 3. The following subsections explain, with examples from literature, the identified enablers under eight categories based on the content analysis of the 59 selected articles in this work. The weight of each enabler refers to the number of articles mentioning that the enabler enables design/planning for digital fabrication adoption.

5.1. Actors

There are 17 types of actors involved in digital fabrication adoption in the design or planning phase as shown in Table 4. The actors are named after their roles or professions. For example, a digital fabrication (DFAB) engineer refers to a person or a group of people who work on the engineering work of digital fabrication technology. A factory commissioner is a person or a group of people who determine the factory layouts and plant setup etc. in, for example, prefabrication off-site factory or an on-site mobile factory. One person can have more than one role.

Amongst all, *AC1 - DFAB engineer* is the most frequently mentioned actor. It is included in 23 articles. For example, Jung et al. (2013) [39] mentions that DFAB engineers enable the development of a robotic rail sliding transport mechanism to transport the robotic bolting device to bolting positions around a building under construction. This is followed by *AC2 - Architectural designer* and *AC3 - Design engineer*. They are included in 17 and 14 articles respectively. AC2 includes architects, spatial designers and interior designers. AC3 includes structural engineers, mechanical electrical and plumbing (MEP) engineers and facade engineers etc. For example, Willmann et al. (2016) [43] mentions that architects and structural engineers enable robotic assembly of a freeform timber roof with the architectural morphologies and structural optimisation through the locally differentiated aggregation of materials respectively. Ng et al. (2021) [15] studies the workflow of one design case where the MEP engineers engaged in the design process so as to enable CNC fabrication for the integrated services. Only a few research studies mentioned actors such as *AC14 - End-user* and *AC16 - Policy-maker* as the enablers. Moreover, most of the real-world projects involved *AC5 - General contractor (GC) and/trade contractor* and/or *AC8 - DFAB contractor* and mentioned less about *AC9 - Platform developer* and *AC11 - DFAB programmer*.

Table 3
Definitions of the enabler categories and their numbers of types in this work.

Category	Definition in this work	No. types
Actor	A person or a group of people with the same role who engage in design/planning for digital fabrication adoption.	17
Resource	A useful or valuable possession or quality of, or provision for design/planning for digital fabrication adoption. This includes equipment and tools, hardware, software, dataset and knowledge that have been required during designing for digital fabrication in the literature.	16
Condition	A situation or medium that influences digital fabrication adoption. This includes a provision of certain resources or an environment etc. that enables design for digital fabrication as demonstrated in the literature.	16
Attribute	A quality, feature or characteristic of a product or a process, which can be a characteristic of the overall value chain from the design process to that digital fabrication process that enables design for digital fabrication. The characteristic can be applied to different elements such as a process or a product.	13
Process	A series of actions, a value chain or a method design for digital fabrication takes in order to achieve a result	19
Artefact	A product/output involved during or after the design for digital fabrication process and directly influences the adoption of digital fabrication to different extents	14
Value	A goal, or a potential achievement/advantage due to digital fabrication adoption.	25
Risk	A potential disadvantage or challenge in digital fabrication adoption that can be addressed and overcome during design development	20

5.2. Resources

16 types of resources are identified as enablers as listed in Table 5. Amongst all, *RE1 - Parametric/computational/data-driven algorithm/machine code* is the most frequently mentioned resource. It is included in 40 articles. For example, in their study on robotic excavator task planning, Seo et al. (2011) [37] emphasises the resource of data-driven algorithms to partition the work area and to generate excavator paths, so that an optimal excavation plan based on 3D models of the work environment can be generated. This is followed by *RE2 - Robotic arm* as included in 36 articles. For example, Hack et al. (2020) [66] and Apolinarska et al. (2021) [11] mention using the robotic arm to manufacture the mesh mould on-site and to automate the tolerance-prone timber assembly process controlled by reinforcement learning respectively. Relatively, very few research mentioned the resources of *RE13 - Industry Foundation Classes (IFC)* and *RE14 - Open-source platform*. Moreover, demonstrator projects and real-world projects involved relatively more *RE6 - Significant human involvement* to different extents.

Table 4
Summary of *actors* as the enablers from selected articles. *Abbreviation:*digital fabrication (DFAB); general contractor (GC).

ID	Actors	Weight	Ref.
AC1	DFAB engineer	23	[3,9,15,39,40,42,46,43,54,61,60,59,57,56,66,65,63,70,71,74–76,78]
AC2	Architectural designer	17	[3,13,15,41,43,49,53,57,58,62,66,68,69,80,78,10,74]
AC3	Design engineer	14	[3,13,15,43,46,48,49,58,61,66,68,69,80,78]
AC4	DFAB design coordinator	10	[10,42,43,46,52,54,69,68,63,70]
AC5	GC/Trade contractor	10	[3,13,15,19,21,45,62,72,76,77]
AC6	Material specialist	10	[57,59,61,63,50,66,67,75,81,87]
AC7	DFAB manager	8	[15,19,66,70,77,79,80,86]
AC8	DFAB contractor	7	[15,45,62,67,72,82,80]
AC9	Platform developer	7	[3,37,52,50,77,80,85]
AC10	Project owner	7	[3,13,15,21,62,70,80]
AC11	DFAB programmer	5	[15,56,57,65,79]
AC12	DFAB BIM coordinator	5	[15,72,77,80,85]
AC13	Supplier/manufacturer	3	[55,64,80]
AC14	End-user	2	[13,42]
AC15	Factory commissioner	2	[39,40]
AC16	Policy-maker	1	[21]
AC17	Surveyor	1	[62]

Table 5
Summary of *resources* as the enablers from selected articles. *Abbreviation:*information and communications technology (ICT); digital fabrication (DFAB); computer numeric control (CNC); artificial intelligence AI); Industry Foundation Classes (IFC); geographic information system (GIS).

ID	Resources	Weight	Ref.
RE1	Parametric/computational/data-driven algorithm/machine code	40	[3,15,37,38,40,41,47,46,45,43,53,52,50,49,54,62,61,60,59,58,57,56,64,69,68,67,66,65,70,71,73,74,78,80,82–87]
RE2	Robotic arm	36	[3,9,11,19,37,40–43,46,47,54,56,59,60,62,63,65–78,81–84,87]
RE3	3D printer	17	[3,9,15,46,48,57,59–61,63,65,66,69,73,75,78,85]
RE4	3D scanner/sensor/camera/ICT	16	[11,37,42,43,56,58,68,67,66,71,72,79,81–83,86]
RE5	BIM-DFAB platforms interface	13	[13,19,45,56,59,61,62,64,70,72,77,80,85]
RE6	Significant human involvement	11	[3,10,13,15,42,44,49,59,67,71,79]
RE7	CNC machines	10	[10,15,41,43,44,48,53,62,58,78]
RE8	Machine Learning/AI algorithm	7	[11,63,68,79,82,83,86]
RE9	Project management system	6	[13,37,39,77,79,84]
RE10	Gantry-type robotic system	5	[3,19,39,43,85]
RE11	Excavator	3	[37,82,86]
RE12	Conveyor belt	2	[13,79]
RE13	IFC	2	[77,80]
RE14	Open-source platform	2	[62,85]
RE15	Unmanned mobile vehicle	2	[71,79]
RE16	GIS	1	[83]

5.3. Conditions

This work also identifies 16 types of conditions as enablers in design for digital fabrication as presented in Table 6. Amongst all, *CO1 - Visual-programming* is the most frequently mentioned condition. It is included in 24 articles. Visual-programming is usually provided during design development for digital fabrication through commercial platforms such as Grasshopper plug-in for Rhinoceros® 3D and Dynamo plug-in for Autodesk® Revit. For example, Lim et al. (2016) [46] and Weng et al. (2021) [85] accent the condition of visual programming using Grasshopper and Dynamo respectively to generate 3D printing paths. This is followed by *CO2 - 3D scanning/RFID/sensing* as included in 16 articles. In their study on assistive micro-room, Linner et al. (2015) [42] underlines that the Radio Frequency Identification (RFID) readers could recognise

Table 6
Summary of *conditions* as the enablers from selected articles. *Abbreviation:*Radio Frequency Identification (RFID); common virtual environment (CVE); common data environment (CDE), extended reality (XR).

ID	Conditions	Weight	Ref.
CO1	Visual-programming	24	[15,41,46,47,50,53,54,58–60,63,65–70,73–75,78,80,85,87]
CO2	3D scanning/RFID/sensing	16	[11,37,42,43,56,58,66–68,71,72,79,81–83,86]
CO3	BIM-based environment	13	[13,15,19,45,61,62,64,70,72,77,80,83,85]
CO4	DFAB digital twin	10	[3,37,47,62,78,79,81,82,85,86]
CO5	Ambient intelligence	7	[3,37,38,42,71,81,82]
CO6	Human-robot interaction	7	[3,19,42,78,79,82,83]
CO7	CVE/integrated platform	6	[3,15,37,62,82,85]
CO8	Remote-control	6	[38,39,42,75,79,82]
CO9	Cloud-based CDE	5	[3,64,78–80]
CO10	Vertical integration	5	[10,13,69,66,78]
CO11	Early contractor involvement	3	[13,15,83]
CO12	Mobile factory	3	[40,71,75]
CO13	Image-based	2	[41,71]
CO14	Immersive XR environment	2	[79,83]
CO15	Monte-Carlo simulation	2	[45,77]
CO16	3D point-cloud	1	[86]

and locate objects and humans in a robust way through integrated sensing. Also, McAlorum et al. (2021) [81] mentions infrared sensing for robotic spray coating on concrete substrates. Moreover, *CO3 - BIM-based environment* is included in 13 articles. This condition involves BIM-based platforms such as Autodesk® Revit. For example, Liu et al. (2021) [80] states that computerised design and prefabrication automation of steel reinforcement was enabled through IFC on Revit BIM-based platform. Only a few research studies include the conditions of *CO9 - Cloud-based common data environment* (CDE), *CO11 - Early contractor involvement*, *CO14 - Immersive Extended Reality (XR) environment* and *CO16 - 3D point-cloud* in their studies. Moreover, the articles that mention about *CO10- Vertical integration* and *CO11 - Early contractor involvement* involved mostly either demonstrator projects or real-world projects.

5.4. Attributes

13 types of attributes were identified as listed in Table 7. Some key attributes are explained with examples as follows. Amongst all, *AT1 - Bespoke/customised design* and *AT2 - Modular* are the most frequently mentioned attributes in design development for digital fabrication as included in 22 articles respectively. In their study on robotic service walls, Issac et al. (2016) [45] accents the attribute of customised design according to various configurations to suit different purposes of usage and the modular wall design with standardised interfaces allows the wall to be easily installed in any residence. Hack et al. (2020) [66] also emphasises the attribute of bespoke design of the doubly-curved mesh mould wall in adopting an in situ robotic fabricator on site. This is followed by *AT2 - Bespoke digital fabrication (DFAB) technology* as included in 21 articles. Bock (2015) [3] reveals that the Japanese firm Taisei adopted single-task construction robotic technology with the attribute of bespoke digital fabrication technology, in particular, to use for automated coating and paintings on facades. Also, other technologies such as Humanoid Robot, Telepresence Robot, as well as window and floor cleaning robots are bespoke digital fabrication technologies specially designed for specific tasks or functions. Only a few research included the attributes of *AT12 - Integrated design- digital fabrication (DFAB) processes* and *AT13 - Risk-sharing/agile contracting*. Moreover, it can be seen many articles that involved demonstrator projects or real-world projects do not explicitly mention *AT4 - Automated design optimisation/generative design*.

5.5. Processes

There are 19 types of processes as enablers in design for digital fabrication as listed in Table 8. Amongst all, *PR1 - Digital fabrication (DFAB) process optimisation* and *PR2 - Prefabrication/off-site* are the most frequently mentioned processes. They are included in 23 articles respectively. In their study on 3D printing workflow, Abou Yassin et al. (2020) [9] emphasises the digital fabrication optimisation process through simulations using agent-based modelling to represent activities carried out in customised environments according to projects. This could help project management to optimise the printing process in terms of costs, usage of resources and project duration. In their study on the robotic band saw, Chai et al. (2021) [74] accents the process of feed rate optimisation for the ruled surface cutting prefabrication process. This is followed by *PR3 - Additive manufacturing* and *PR4 - Robotic assembly* as process enablers to adopt digital fabrication. They are included in 22 and 20 articles respectively. In their study on resource-efficient design tools for digital fabrication, Craveiro et al. (2017) [50] states the process of additive manufacturing to test with varied material composition for lightweight components, one used a granulated cork and another one used expanded clay. Only three articles include *PR18 - Lean* process enabler. Moreover, articles that mention about *PR4- Robotic assembly* and *CO11 - Early contractor involvement* involved mostly either demonstrator projects or real-world projects.

5.6. Artefacts

Besides, 14 types of artefacts are included in literature as listed in Table 9. Amongst all, *AR1 - Digital fabrication (DFAB) physical mockup* is the most frequently mentioned artefact. It is included in 39 articles. For example, in the study on additive manufacturing, Datta et al. (2016) [48] underlines the artefact of scaled prototypes of physical mockup using papers and timber to optimise the production. Liu et al. (2021) [79] also emphasises this artefact in the process of using collaborative unmanned ground vehicle robots. This is followed by *AR2 - Freeform architecture* and *AR3 - Bespoke digital fabrication (DFAB) tools*, which are included in 21 and 19 articles respectively. In the study on compression-only concrete shell design, Block et al. (2017) [49,66] demonstrates the artefact of freeform concrete envelope structure with robotic actuators for solar shading. Bespoke digital fabrication tools refer to dedicated tools as products developed in research that enable digital fabrication adoption. Aagard et al. (2020) [67] presents the artefact of bespoke technology with a band saw on a six-axis robot arm to produce curved pieces of a crooked log informed by each log's particularities. Only one article includes the artefact *AR13 - Digital twin for facility maintenance (FM)*. Moreover, the artefacts *AR2 - Freeform architecture* and *AR3 - Bespoke DFAB tools* are mentioned in several demonstrator projects and real-world projects.

5.7. Values

Furthermore, 25 types of values are identified as enablers as listed in Table 10. Amongst all, *VA1 - Reducing human dependency* is the most frequently mentioned value as included in 34 articles. For example, Willmann et al. (2016) [43] emphasises the value of minimising human dependency to improve efficiency and flexibility to adapt and react to different design situations. This is followed by *VA2 - Reducing time/ improving efficiency* and *VA3 - Improving quality/performance*. They are included in 28 and 26 articles respectively. Yabanigul et al. (2021) [87]

Table 7
Summary of *attributes* as the enablers from selected articles. *Abbreviation:*digital fabrication (DFAB); level of development (LOD).

ID	Attributes	Weight	Ref.
AT1	Bespoke/customised design	22	[10,15,38,41,43,45,46,49,57,59,60,62,63,65–69,73,74,78,87]
AT2	Modular	22	[10,11,13,15,38,40,44–46,48,52,55,58,62,65,68,69,73,74,78,79,84]
AT3	Bespoke DFAB technology	21	[3,15,38,42,43,46,49,52,54,57,59,61,65–67,70,74,75,78,84,87]
AT4	Automated design optimisation/generative design	15	[38,41,45,49,50,53,57,58,60,65,69,70,73,78,87]
AT5	Human independent	14	[9,38,56,60,63,65,68,69,71,74,75,77,84,85]
AT6	High LOD BIM/model data	12	[15,43,49,61,62,66,67,69,72,77,80,85]
AT7	Highly standardised	11	[11,13,71,77,79–82,84–86]
AT8	Industrialised	11	[3,13,15,38,39,61,62,75,77,84,85]
AT9	Mobile	6	[38,40,71,75,77,84]
AT10	Human assistance	4	[11,15,41,42]
AT11	Sequential design-DFAB process	3	[73,77,80]
AT12	Integrated design-DFAB process	2	[15,85]
AT13	Risk-sharing/agile contracting	1	[15]

Table 8
Summary of *processes* as the enablers from selected articles. *Abbreviation:*digital fabrication (DFAB); design for manufacture and assembly (DfMA).

ID	Processes	Weight	Ref.
PR1	DFAB process optimisation	23	[3,41,9–11,15,46,47,49,54,56,60,66–68,70,74,77,78,84–87]
PR2	Prefabrication/off-site	23	[3,10,11,15,13,38,40,41,43,45,46,53,55,58,62,63,65,67,68,73,74,78,80]
PR3	Additive manufacturing	22	[3,9,15,46,48,50,51,54,56,57,59–61,63,65,66,69,73,75,77,81,85]
PR4	Robotic assembly	20	[3,11,13,38–41,43,47,49,52,55,56,62,68,70,72,76,78,84]
PR5	Modularisation	19	[10,11,13,15,37,38,40,44,45,52,53,55,58]62[68,73,74,78,84]
PR6	Post-rationalisation/design optimisation	19	[10,15,37,41,43–45,48–50,52,58,60,62,63,66,73,74,85]
PR7	Subtractive manufacturing	17	[10,15,37,41,43,44,48,53,58,60,62,67,73,74,78,80,87]
PR8	On-site DFAB	14	[3,37,39–41,55,66,71,72,75,79,82,85,86]
PR9	DfMA for DFAB process	13	[3,10,15,40,46,49,60,65,67,73,74,78,80]
PR10	Material testing	11	[54,57,59,61,63,65–67,74,75,81]
PR11	Mass-customisation	9	[3,13,15,38,45,62,67,73,87]
PR12	Path-planning	8	[11,37,75,77,83,85–87]
PR13	Platform development	8	[3,37,50,52,64,80,84,85]
PR14	Providing services/operations	6	[3,13,42,79,82,86]
PR15	Robotic pickup/selection	4	[13,71,84,86]
PR16	Excavation/transportation	4	[37,79,82,84]
PR17	Data mapping/augmentation	3	[71,79,80]
PR18	Lean	3	[13,40,82]
PR19	Robotic drilling	2	[72,74]

Table 9
Summary of *artefacts* as the enablers from selected articles. *Abbreviation:*digital fabrication (DFAB); level of development (LOD); performance (perform.); facility maintenance (FM).

ID	Artefacts	Weight	Ref.
AR1	DFAB physical mockup	39	[3,11,15,40–43,46–50,52–54,56–61,63,65–69,71,73–75,10,78,79,81,84–87]
AR2	Freeform architecture	22	[10,15,43,46,48,49,53,54,57,58,60,62,63,65–69,74,75,78,87]
AR3	Bespoke DFAB tools	21	[3,38,42,43,46,49,52,54,57,59,61,65–67,70,74,75,78,79,84,87]
AR4	Performance-based design	19	[10,13,15,39,49,50,52,60,63,65,66,68–70,74,77,81]
AR5	DFAB virtual mockup	18	[3,9,11,41,47,49,59,60,65,66,70,74,75,77,78,84,86,87]
AR6	Configurators/kit-of-parts	12	[10,13,15,38,45,58,62,66,68,73,78,84]
AR7	High LOD BIM for DFAB	11	[15,43,49,61,62,66,69,72,77,80,85]
AR8	Bespoke DFAB platform	8	[3,37,42,50,52,80,84,85]
AR9	Automated production workflow	7	[13,71,73,82,84,85,87]
AR10	2D drawings for production	2	[15,80]
AR11	Human-readable perform. report	2	[15,77]
AR12	Robotic home assistance	2	[3,42]
AR13	Digital twin for FM	1	[13]
AR14	Task schedule planning	1	[77]

Table 10
Summary of *values* as the enablers from selected articles. *Abbreviation:*design for disassembly (DfDisAssembly); return on investment (ROI).

ID	Values	Weight	Ref.
VA1	Reduce human dependency	34	[3,10,11,13,15,37–43,50,51,54,56,61,62,65,68,9,70–73,76–81,84–86]
VA2	Reduce time/improve productivity/efficiency	28	[3,9,10,13,15,19,21,39–41,43,45,46,51,61,62,66,70,72–76,79,80,83–85]
VA3	Improve quality/performance	26	[3,11,13,15,21,43,48–51,57,58,62,63,66,67,71,72,74,75,78–81,85,87]
VA4	Material/energy saving/reduce CO2/waste	24	[9,13,15,21,43,46,49,50,54,55,57–59,61,63–67,73,74,83,85,87]
VA5	Increase arch complexity/design customisation/creativity	24	[3,10,15,41,43–46,49,53,57,58,60,63,65,66,69,73–75,78,85–87]
VA6	Reduce cost	19	[3,9,21,40,41,46,51,53,55,61–64,66,67,70,73,85,87]
VA7	Reduce construction complexity	14	[3,15,19,41,45,46,53,61,62,67,73,84,85,87]
VA8	Knowledge transfer	13	[3,13,15,21,47,49,55,59,62,64,67,66,81]
VA9	Allow traceable/linked data	12	[11,13,37,62,66,72,79–82,85,87]
VA10	Reduce errors/constraints	11	[13,15,43,45,64,73,79,80,82,85,86]
VA11	Systemic design solutions	9	[3,13,15,50,49,60,68,66,65]
VA12	Market-driven	8	[3,13,15,19,38,40,42,55]
VA13	Improve site safety	7	[39,77,79,80,82,83,85]
VA14	Integrate supply chain	7	[3,13,21,49,55,62,66]
VA15	Circular construction/DfDisAssembly	5	[13,38,53,62,78]
VA16	Improve human wellbeing	5	[3,13,42,79,83]
VA17	Reduce transportation complexity	4	[13,15,40,79]
VA18	Enable life cycle assessment	3	[13,15,81]
VA19	Increase profit/ROI	3	[55,62,76]
VA20	Location independent	3	[15,40,84]
VA21	Accommodate late design changes	2	[52,80]
VA22	Easy to maintain	2	[13,79]
VA23	Contemplating future of work	1	[83]
VA24	Environmental adaptive	1	[82]
VA25	Reduce disruption due to hazards	1	[83]

accents the value of better surface quality with the robot program because it offers a zoning parameter, which keeps the robot arm running without touching the interval planes. Also, *VA4 - Material/energy saving/ reduce CO2/waste* and *VA5 - Increasing architectural (arch) complexity* are included in 24 articles respectively. Mechtcherine et al. (2019) [61] underlines the value of lower carbon footprint because the concrete materials used have a lower cement content in comparison to the most known examples of printable concrete. Ng et al. (2021) [15] emphasises the value of achieving bespoke architectural geometry in the design case using CNC machines because it allows digital fabrication based on the data of bespoke 3D geometries provided by the architects in BIM. Moreover, several demonstrator projects involve *VA3 - Improve quality/ performance* and *VA5 - VA5 - Increasing architectural (arch) complexity*.

5.8. Risks

Last but not least, 20 types of risks were identified from literature as listed in Table 11. Amongst all, *RI1 - Increasing uncertainty in production* and *RI2 - Performance compromise/uncertainty* are the most frequently mentioned risks as mentioned in 15 articles respectively. For example, Tepavcevic et al. (2017) [53] emphasises the risk in the assembly process with the rows that connect vertices with singular vertices. This could be solved by introducing a new direction of rows. Also, Chai et al. (2021) [74] mentions the risk that errors could occur if the cutting tasks conducted by the band saw exceed the processing capacity. This would also damage the saw blade and the saw itself. This is followed by *RI3 - Increasing cost/investment uncertainty*, which is included in 9 articles. Linner et al. (2020) [19] indicates the risk that investment uncertainty in terms of performance such as work processes might hinder digital fabrication adoption. This risk could be addressed by the *cost benefit analysis*, as well as an elaborated and a *commonly agreed upon set of criteria* for the robot and the development process. Nevertheless, most selected articles (42 out of 59) did not explicitly mention the risks as potential obstacles in digital fabrication development and adoption. Risks in design for digital fabrication still require more research to investigate in detail. Relatively, more risks are mentioned in demonstrator projects mentioned risks.

6. Enablers frequency network

This work further presents the results of a frequency analysis through the literature review as a frequency network in an adjacency matrix with heat map visualisation as shown in Fig. 3. This aims to provide a high-level validation of the non-directional relationships amongst the enabler categories by capturing how strong the relationships between any two enablers (e.g. enabler X and enabler Y) through revealing their frequency weights in each cell (X,Y) in the matrix.

The frequency weight between enabler X and enabler Y refers to how many articles, amongst all 59 articles reviewed in this work, mention them in the process of design for digital fabrication. While the heat map visualisation uses a colour scale to differentiate the different weight categories ranging from low to high [36]. When the frequency weight is low, the red colour is lighter, which indicates a looser relationship between the enablers. For example, the weight of the relationship of (AC3, AC6) is 2 frequency weight "2" is indicated in the cell (AC3,AC6) on the third row and the sixth column, where both rows and columns are under the category actors. This means that the enablers AC3 - Design engineer and AC6 - material specialist are included together in two articles. The cell is coloured in light red.

This frequency network indicates how often two enablers in the same or different categories are mentioned in a process of design for digital fabrication in the existing literature. A limitation should be noted here, that the work presents a non-directional relationship between the enablers. This simplies the network and provide a high-level investigation of the network studies, but future research such as case-based process mapping research should be undertaken to explore the cause-and-effect relationship in detail.

Based on the findings, most of the time, a high-frequency weight can be found on the top left corners of the category pair. For example, weights of 31 and 26 are found in (RE1,AR1) and (RE1,RE2) respectively. However, in some cases a high weight can be found in other areas, for example, (AR1, VA5) has a weight of 22. Sometimes, a high weight is because two enablers possess a similar topic. For example, the frequency weight of (AT2,PR5) is 17. However, articles that include attribute AT2 - Modular do not necessarily include the process PR5 - Modularisation. For example, Lim et al. (2016) [46] emphasises the modular attribute in their study on the printing paths of a sandwich panel module. However, their study does not accent the process of modularisation.

From a high-level perspective, the matrix shows that actors have a strong relationship with processes and values, where the clusters Actor-Process and Actor-Value have relatively more red cells than other actor's clusters. Conditions have relatively weak relationships with other enabler categories. Also, processes have strong relationships with artefacts and values. While resources have strong relationships to processes and values. Artefacts seem to have strong relationships with all other enabler categories except risks. Risks also show a weak relationship with actors and conditions and artefacts. Moreover, attributes, processes, artefacts and values show strong relationships within themselves. This

Table 11
Summary of *risks* as the enablers from selected articles. *Abbrevation:*digital fabrication (DFAB).

ID	Risks	Weight	Ref.
RI1	Increase uncertainty in production	15	[9,19,46,49,53,54,61–63,65,68,74,79,81,87]
RI2	Performance compromise/uncertainty	15	[46,53,49,54,56,61,63,65,66,71,74,79,81,85,87]
RI3	Increase cost/investment uncertainty	9	[9,15,19,40,62,72,10,76,83]
RI4	Increase management complexity	8	[9,19,43,49,56,71,79,83]
RI5	Location dependent/site constraint	8	[21,42,43,47,49,52,61,71]
RI6	Require workforce training	8	[19,47,55,61,62,73,79,83]
RI7	Rely on DFAB specialist	7	[15,19,61,72,76,78,83]
RI8	Rely on DFAB technology	7	[9,19,61,62,66,74,87]
RI9	Rely on digital system	6	[50,62,71,72,77,85]
RI10	Stakeholders sceptical attitude	6	[15,19,55,62,79,83]
RI11	Machine error/immature technology	5	[71,74,79,83,87]
RI12	Delivery/business model/work culture	4	[15,21,79,83]
RI13	Increase labour work	4	[9,19,52,62]
RI14	Rely on precise planning	4	[61,62,66,72]
RI15	Design compromise/over standardised	3	[68,74,77]
RI16	Increase material usage/waste	3	[10,19,66]
RI17	Market access complexity/uncertainty	3	[15,19,83]
RI18	Regulatory/legal concern	3	[21,55,83]
RI19	Production/assembly restriction	2	[15,40]
RI20	Work safety concern	2	[61,83]

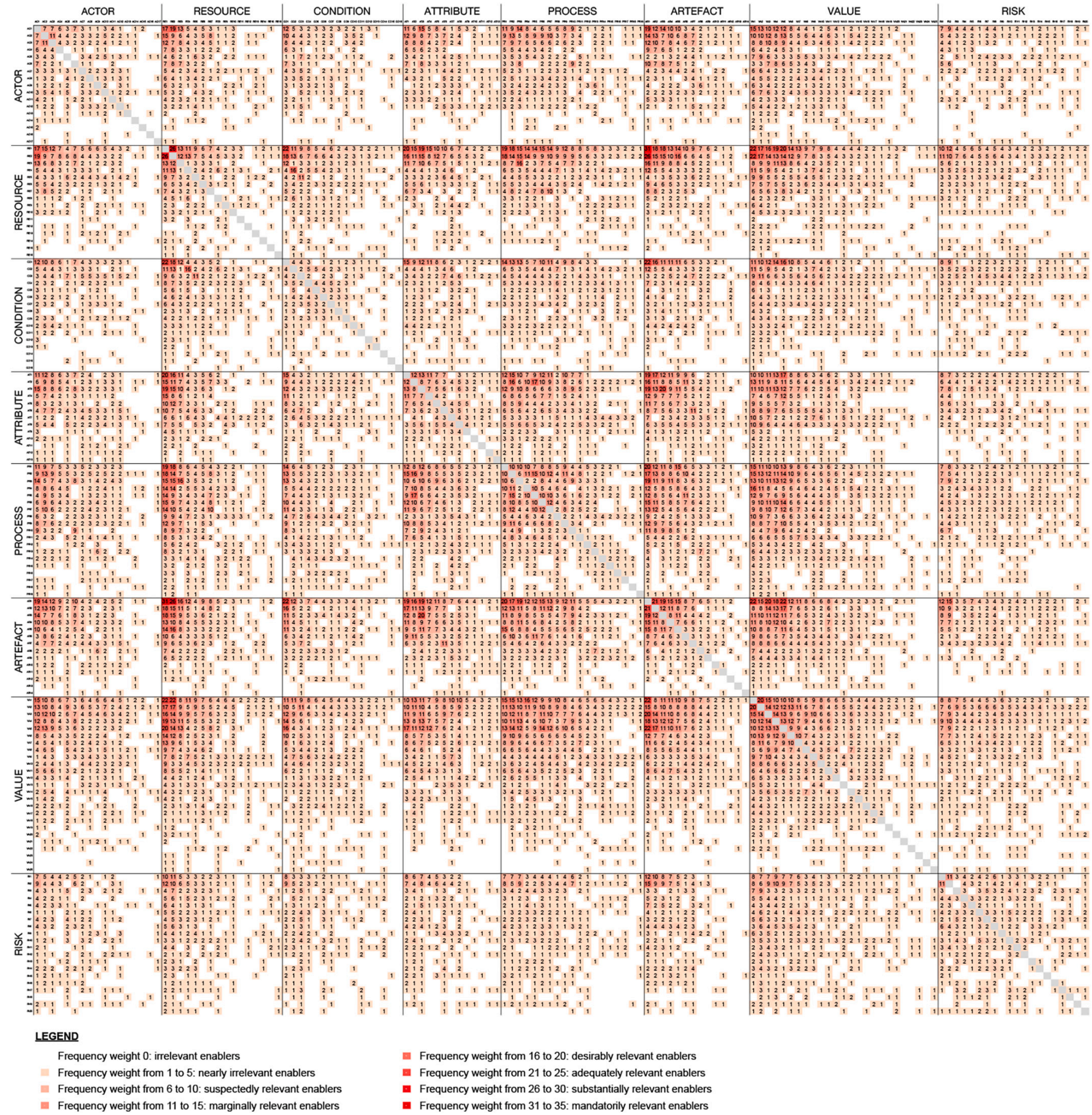


Fig. 3. Enablers frequency network in an adjacency matrix. The higher the weight, the darker the red colour in a cell; when the frequency weight is "0", the cell is shown as blank and coloured in white.

means, for example, it seems that values have a strong relationship within the category; while it seems that actors have a weak relationship within the category.

7. Relational ontology networks

This work further presents the studies of relational ontology networks of the identified enablers through the lens of actor-network theory based on data from the systematic literature review and the frequency network analysis [28,29]. This aims to investigate how enablers are interrelated to one another to enabler a specific focus or a group of specific foci. Moreover, this work presents that a network of enablers can be illustrated in an onion diagram for data visualisation. In the onion diagram, the frequency weights between the focal enabler(s) are represented by a hierarchy based on the data from Section 6 of the onion layers.

This section presents three networks as examples for researchers and practitioners to comprehend the relational ontology networks of the enabler foci - circular construction focus, business model focus and digital twin in industrialisation focus - that can address the industry problems of *low sustainability performances due to poor material consumption*, *low capital returns* and *low productivity and innovation* respectively. These three examples are merely illustrative of how the relational ontology can work. Any focal topic could be chosen and a relational ontology could be developed around that topic. They serve as a reference for researchers and practitioners to consider in designing for digital fabrication in future.

7.1. Network Example 1: circular construction focus

To investigate the relational ontology network in design for digital fabrication with the focus on *circular construction*, this work maps the focal enabler *VA15 - Circular construction/DfDisAssembly* as the core and the network in an onion diagram as shown in Fig. 4. In this work, the relational ontology network studies and the onion diagrams are derived based on the findings from the literature review and the frequency analysis. In this work, *circular construction* is defined as a design-driven resilient system in construction that eliminates waste and pollution, circular products and materials and regenerates nature after disassembly; while *Design for DisAssembly (DfDisAssembly)* is defined as the value chain to successfully transform the disassembled system to values. The diagram has five onion layers with a total of 84 enablers, where each has a frequency weight of one or more with the core (VA15). The network shows that the two processes - prefabrication and modularisation - enable circular construction in design for digital fabrication. Besides, architectural designer actor, parametric resource, modular attribute, robotic assembly process, configuration artefact and reduce human dependency value enable circular construction to different extents. Overall, this network study provides an insight that many processes and values are relevant to the focus on circular construction in design for digital fabrication.

7.2. Network Example 2: business model focus

To investigate the relational ontology network with the focus on *business model*, this work maps the focal enabler *VA19 - Increase profits/return on investment (ROI)* as the core and the network in an onion diagram as shown in Fig. 5. In this work, *business model* is defined as a plan for the successful operation of a business with identified revenue as a return on investment. The diagram has three onion layers with a total of 50 enablers, where each has a frequency weight of one or more with the core. The network shows that the robotic assembly process can help to enable profits based on literature. Besides, contractor actor, parametric resource, modular attribute, prefabrication and modularisation processes, values of reducing human dependency, time and cost, knowledge transfer and supply chain integration, as well as risks of increasing cost, workforce training and stakeholder sceptical attitude can also help to enable profits to different extents. Overall, the network provides an insight that many values and risks are relevant to the focus on business model in regards to profits.

7.3. Network Example 3: digital twin in industrialisation focus

To investigate the relational ontology network in design for digital fabrication with *digital twin in industrialisation*, this work maps the focal enablers *CO4 - Digital fabrication in digital twin* and *AT8 - industrialised* as the core and map the network in an onion diagram as shown in Fig. 6. In this work, *digital twin* is defined as the combination of computational models and real-world systems with the aim to provide a real-time digital representation. Also, *industrialisation* is defined as an intentionally broad category of processes, which includes offsite prefabrication, modular assemblies and DfMA, adopted on a large scale. The diagram has three onion layers with a total of 80 enablers, where each has a frequency weight of one or more with the core. The network shows that parametric resource, common data environment condition and the values of reducing human dependency, time, cost and construction complexity, as well as improving quality enable industrialisation using a digital twin. Besides, five BIM-based enablers are identified on the second layer. This implies that BIM-based design and construction environment can enable this focus in design for digital fabrication. Overall, the network shows that many values and processes are highly relevant to the topic. This is followed by resources, as well as actors. Conditions, attributes, artefacts and risks show relatively weaker relationships with the core. Also, some enablers such as design engineer actor, CNC machine resource and automated production workflow artefact show a weak relationship with other enablers in the network.

This network shows that the edges between enablers are more compact than in the other two network examples. It is partly because there are two focal enablers in the core and partly because there are seven enablers on the innermost layers, where each of them is fully related to all enablers in the network. Also, all enablers on the outermost layers are related to more than half of the enablers on the other two inner layers. This compact network indicates that design for digital fabrication with digital twin in industrialisation could require close integration of various aspects. Moreover, based on the diagram, many values and risks are associated with this focus. There are advantages and challenges and thus further investigations of the approaches.

8. Discussion

8.1. Process modelling for designing and managing construction automation

To illustrate how the findings of this work can integrate the enablers of design for digital fabrication into the overarching process of construction automation management, we next discuss a proposed process model approach for designing and managing construction automation. This process model comprises a focus-oriented and holistic model-based approach. It standardises the construction process to achieve or accomplish the specified focus and the associated enablers.

Process modelling provides an overview or understanding of time-regulated process sequences regarding certain use-cases to investigate opportunities for improvement and eventually bottlenecks along the way. Recent scholarship such as O'Connor et al. (2014) [25], Chen et al. (2018) [20], Ng et al. (2020) [6] and Linner et al. (2020) [19] study process modelling framework which indicate the value chain requirements of construction automation and innovation at different stages of project from design to implementation. This work presents the proposed process model in reference to the literature to assist researchers and practitioners to design for digital fabrication.

Thereby, this proposed process model shows how to reach a project goal with the specified focus by following the process sequences accordingly.

Also, it embeds the enablers in a potential real-world use-case framework and enables chronological documentation of the value chain for further optimisation of system interfaces etc. The proposed process model with seven steps is illustrated in Fig. 7 and the steps are explained as follows. It represents an agile and adaptive framework for validating the enablers and the corresponding network studies, as well as implementing the findings of this work for managing construction automation in real-world projects.

1. Process kick-off: The focus of the construction project is first defined to identify the associated enablers from the adjacency matrix and map the corresponding relational ontology network(s) of the focus.
2. Process discovery: The identified enablers from Step 1 are integrated into a pre-defined architecture of the design and construction process for the specific use case.
3. Process identification: The pre-defined process with the integrated enablers, namely *as-is process model*, is validated by a real-world use-case test for data collection.
4. Process analysis: The collected data from the real-world use-case test can thus be evaluated to provide insights on weaknesses,

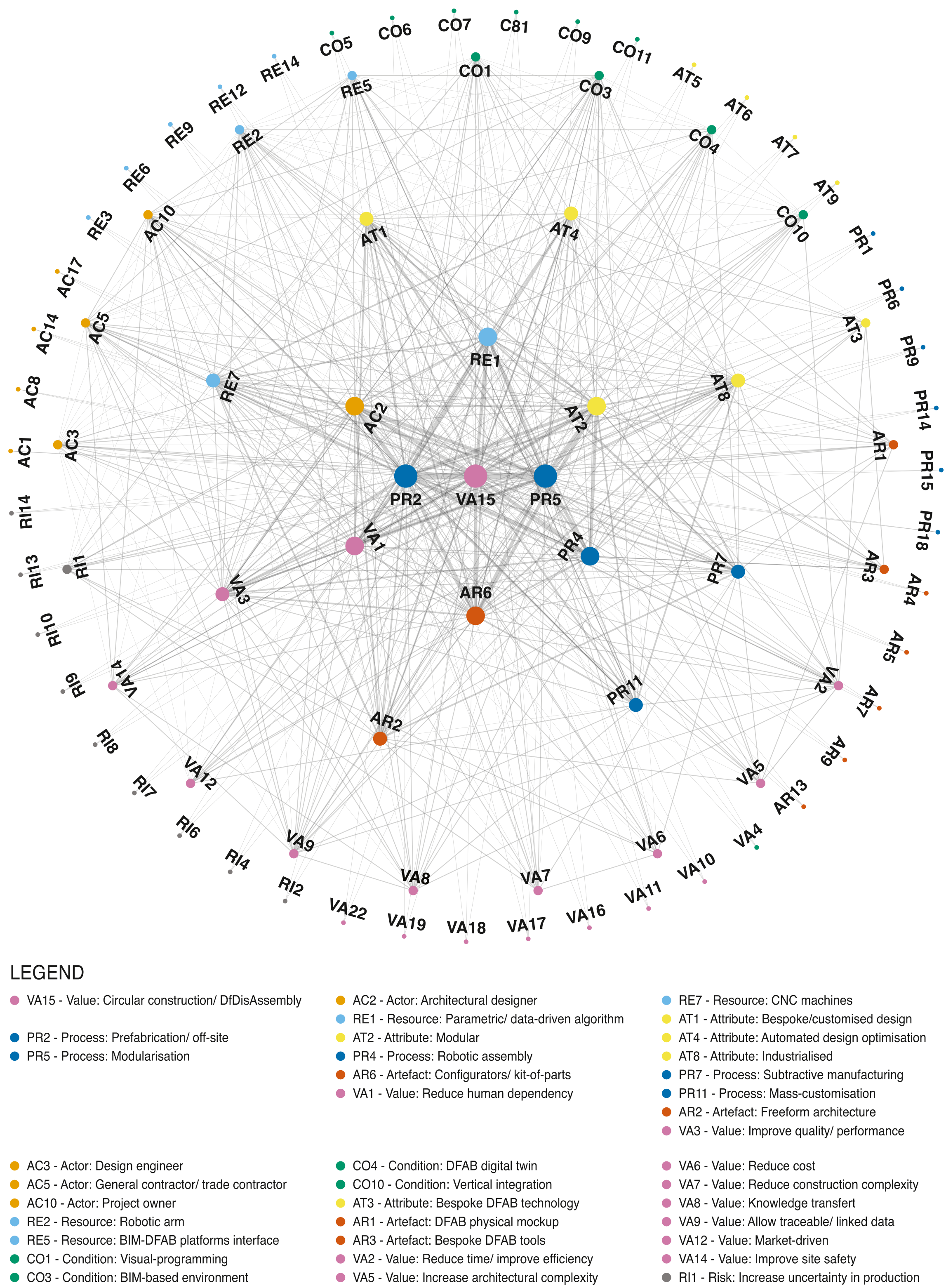


Fig. 4. The relational ontology network in design for digital fabrication with the focus on circular construction. The focal enabler *VA15 - Circular construction/Design for DisAssembly (DfDisAssembly)* is the core in this network. The innermost layer with the highest frequency weight of five contains two enablers *PR2 - Prefabrication/ off-site* and *PR5 - Modularisation*. The second inner layer with a frequency weight of four contains six enablers. The third inner layer with a frequency weight of three contains eight enablers. The fourth inner layer with a frequency weight of two contains 21 enablers. Last but not least, outermost layer with the frequency weight of one contains 47 enablers. This diagram merely includes the edges from the enablers on the outermost layer to the enablers VA15, PR2 and PR5 for better legibility. *Abbreviation:*digital fabrication (DFAB).

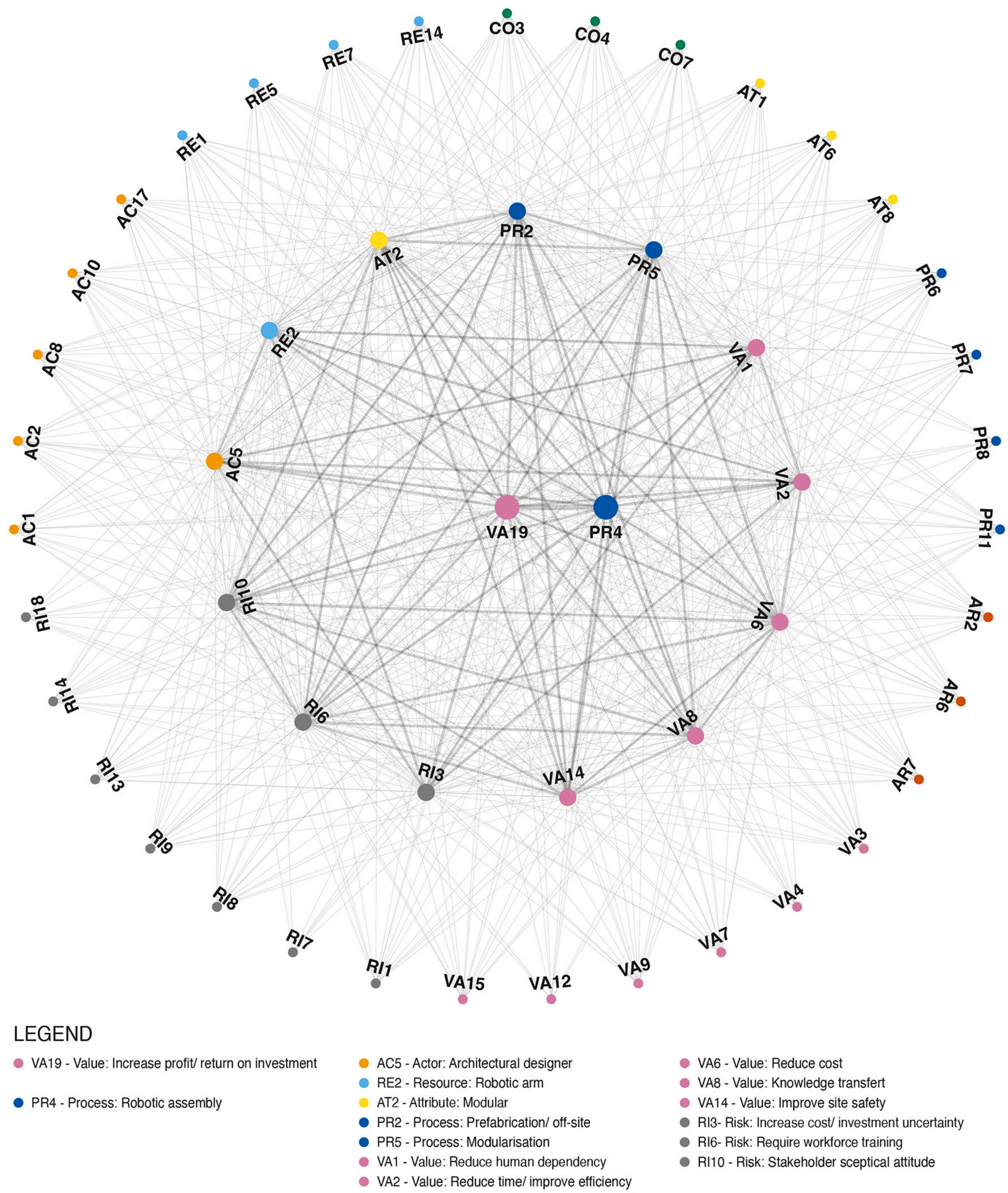


Fig. 5. The relational ontology network in design for digital fabrication with the focus on business models in terms of profits. The focal enabler *VA19 - Increase profits/return on investment (ROI)* is the core in this network. The innermost layer with the highest frequency weight of three contains one enabler *PR4 - Robotic assembly*. The second inner layer with a frequency weight of two contains thirteen enablers. The outermost layer with a frequency weight of one contains 34 enablers: six values, seven risks, five actors, four resources, four conditions, three conditions, three attributes and three artefacts. The edges between the enablers on the outermost layer are not shown for better legibility.

opportunities, and their impacts. Furthermore, the reliability of each enabler to the defined focus is evaluated.

5. Process implementation: The *to-be process model* is then developed through a redesign of the as-it process model with the selected reliable enablers and the identified impacts from Step 4.
6. Conformance and performance insights: The newly developed to-be process model is, hence, evaluated once more with the same real-world use case test (adopted in Step 3) to provide further insights on conformance and performance through process monitoring and control.
7. Standardisation, monitoring and execution: The resultant process can be standardised for executions in the projects. The business model of the process can also be established accordingly.

8.2. Contribution to theory

This work presents enabler identification and investigation of relational ontology networks through the lens of actor-network theory. The data source covers a wide spectrum of design/planning for digital fabrication research and projects in practice and various types of digital fabrication implementation. In theory, this work contributes to

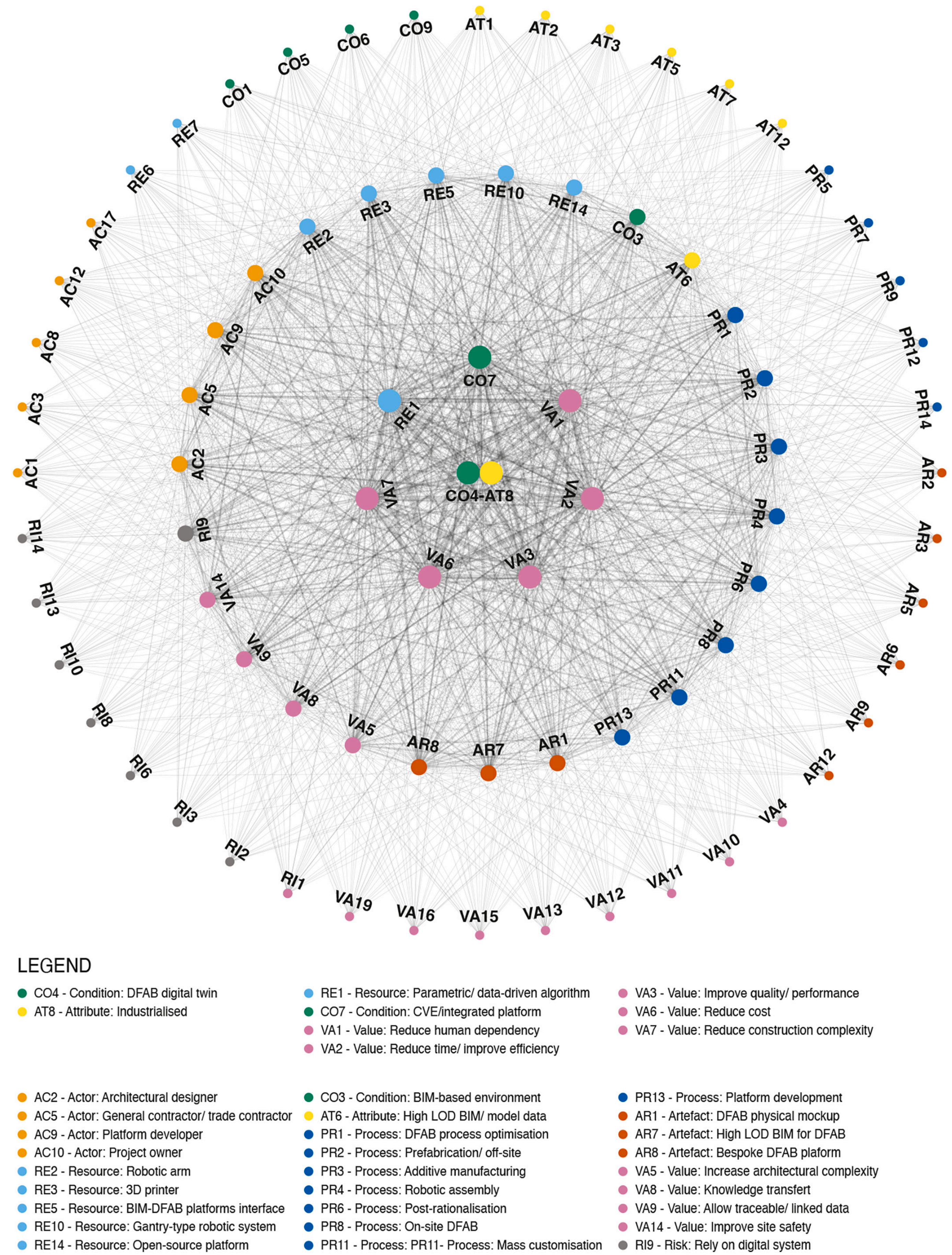


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Fig. 6. The relational ontology network in design for digital fabrication with digital twin in industrialisation. The focal enablers *CO4 - Digital fabrication in digital twin* and *AT8 - industrialised* are the core in this network. The innermost layer with the highest frequency weight of three contains seven enablers. The second layer with a frequency weight of two contains 27 enablers: eight processes, five resources, four actors, four values, three artefacts, one attribute and one risk. The outermost layer with a frequency weight of one contains 44 enablers:eight values, eight risks, six attributes, six artefacts, five actors, five processes, four conditions and two resources. The edges between the enablers on the outermost layer are not shown for better legibility. *Abbreviation:*digital fabrication (DFAB), common virtual environment (CVE), level of development (LOD).

researchers who are developing digital fabrication technologies, designing for the adoption of digital fabrication and researching management for automation in construction to provide a consistent collection of enablers captured in the past scholarship, as well as the associated network and process model for design for digital fabrication in their future research work.

This work not only presents a methodology of enabler identification, but also demonstrates how researchers can map a relational ontology network on an onion diagram based on the lists of enablers and the adjacency matrix through systematic literature. This onion diagram mapping method can help to visualise the hierarchy of key enablers through layering, as well as indicating the weights of relationships through edges between nodes of enablers. This adopts the actor-network theory to illustrate the dynamic ways, which the relationships between enablers (a.k.a. actants) are forged and negotiated. The network studies provide a theoretical basis for researchers to further investigate the interrelationships amongst the enablers for their future research. With the methodology and findings in this work, researchers can select the focal enabler(s), in which they are interested, to investigate and develop their relational ontology networks based on literature. Furthermore, this work proposes a process modelling to implement enablers and networks on projects, and presents an outlook on future research about design for digital fabrication.

8.3. Contribution to practice

Furthermore, this study of the enablers aims to assist industry practitioners to understand the requirements for changes in the value chains, so as to enable digital fabrication adoption to go beyond its seed phase and encounter adoption on a larger scale. This work identifies 140 enablers under eight categories, namely *actors, resources, conditions, attribute, process, artefact, value and risk* in design for digital fabrication through a systematic literature review. The lists of enablers serve as a reference for project stakeholders to prepare what roles (*actors*), what *resources*, what *conditions*, what *attributes* and what *processes* should be involved, as well as what *artefacts*, what *values* and what *risks* can be expected in design for digital fabrication.

Moreover, the findings in the adjacency matrix in Fig. 3 based on the frequency analysis and the relational ontology network examples in Section 6 and Section 7 provide insights for project stakeholders to understand how the enablers are inter-related to each other in design for digital fabrication to different extents. For example, based on Fig. 4, when a project stakeholder would like to focus on a sustainable adoption of digital fabrication to foster design for disassembly and circular construction, prefabrication and modularisation processes are recommended in the design or planning phase. Also, architects can play an important role in design for digital fabrication; the robotic assembly process could be helpful to achieve goals of design for disassembly; stakeholders can also expect to develop configurations or kit-of-parts; the potential values delivered could be reducing human dependency. Moreover, the proposed process model in this work offers a potential workflow for practitioners to design for digital fabrication in construction projects in current practice.

In summary, this work provides a twofold contribution to theory and practice, where researchers and industry practitioners can further design to adopt digital fabrication in construction projects. The findings address the need for adopting digital fabrication and foster construction automation, as well as how to enable design for digital fabrication so as to existing problems in the architecture, engineering and construction industry.

8.4. Limitations and potential future research

This research has several limitations as follows. Firstly, the keyword search in this work merely filtered articles through exact phrases. To generate more detailed and elaborated results the keyword search can be adjusted to find alternate word endings ("*") as well. However, the authors remain confident that the search was sufficiently broad, and the key literature on the topic has been captured. Secondly, the enablers and the networks are identified and developed based on many recent publications. Digital fabrication is still early in development, as shown in Table 2. It is possible that in the next few years as digital fabrication publications become more frequent, the enablers for design may also evolve or new enablers can be identified. Thirdly, the literature review could involve a risk of coding bias. Through the systematic approach described, we have attempted to counter both our own bias in identifying enablers or bias found in the sample of literature (e.g., a bias towards over description of technocratic solutions rather than actor-based solutions could be present in the literature). Fourthly, research in the field of digital fabrication is often relatively exclusive due to competition and the lack of publication of scientific articles sometimes present in the field of architectural research. In future research, the findings can be compared to the other industries, such as the medical industry, using the same research method to validate the reliability of the findings.

8.4.1. Future research on design for digital fabrication

To extend this research on design for digital fabrication, the authors proposed future research topics to extend this work and verify the enablers as follows. The findings can be structured and subdivided into more underlying categories according to, for example, design stages, digital fabrication methods and construction purposes, to develop a more detailed basis for further process modelling. Similarly, the synthesised and categorised enablers can be further sub-categorised according to their types (e.g. stakeholder, method, robot, machine, digital 3D-model, physical 3D-model, file format, information and communications technology (ICT) etc.) within the eight categories. Also, the enablers can be sub-categorised based on the types of design digital fabrication projects (e.g. seed phase prototyping, demonstrator projects and real-world projects), as well as the research methods used in the literature. This can provide a more in-depth analysis of the enablers and break down the enabler catalogues to suit readers' needs. Moreover, some enablers (e.g. 3D point-cloud and immersive Extended Reality (XR) environment conditions, lean process and digital twin for facility management artefact) appear to be less mentioned by the literature. This might not reflect that they are less needed by real-world projects than those which appear more often in the literature.

8.4.2. Future research on network studies regarding construction automation

In this work, the identified frequency weights between two enablers are non-directional. Future research can explore the convergence and divergence of their relationships, as well as closeness and betweenness in network science. In this regard, the relationships can be expressed more detail with the considerations of information flow, human resource flow, cash flow and also communication flow (type/format of information transfer) etc., which are supplementary to understanding

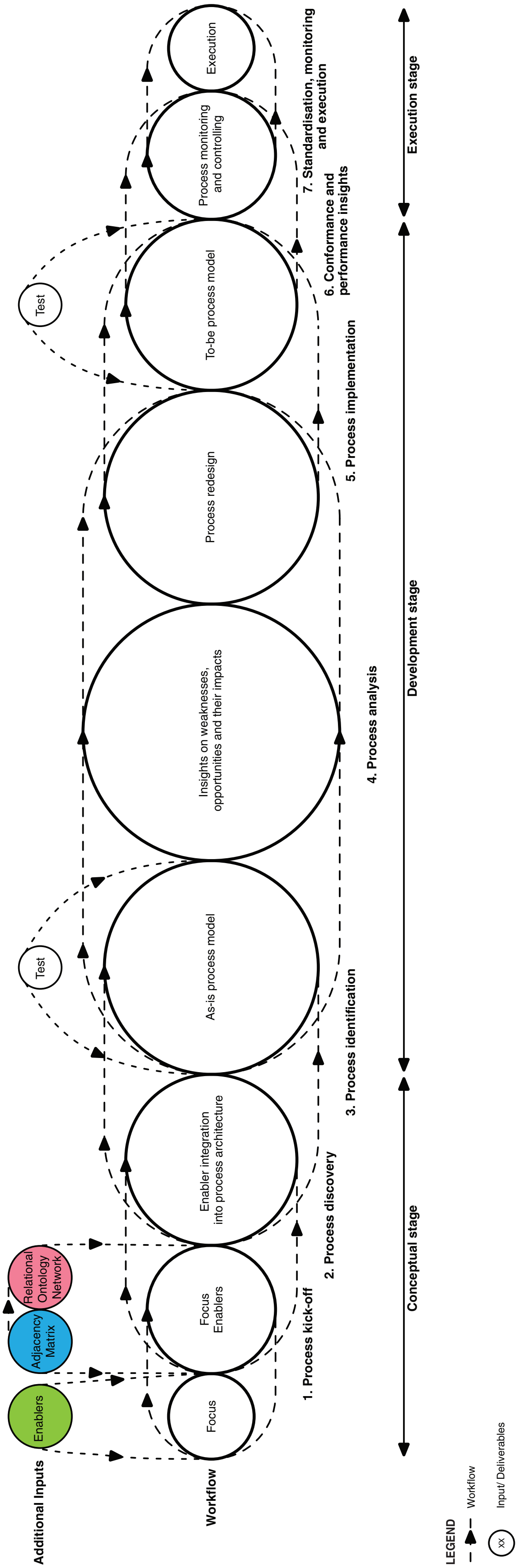

Fig. 7. The process model with seven steps for designing and managing construction automation in this work. The inputs of the relevant enablers, the adjacency matrix and the relational ontology network based on this work in the process model are highlighted in green, blue and fuchsia respectively.

the relative distance and its relations in accordance with the allocated enablers. Also, the authors understand that most research, which adopts the actor-network theory approach, conducts empirical case studies instead of merely a literature review. Hence, this work proposes future research to validate and further investigate relational ontology networks, as well as the proposed process model through in-depth empirical case studies in practice.

9. Conclusions

This work identifies 140 enablers under eight categories - 17 actors, 16 resources, 16 conditions, 13 attributes, 19 processes, 14 artefacts, 25 values and 20 risks - based on a five-stage systematic literature review of 59 journal articles published between 2011 to mid-2021. In each category, the enablers are listed with their source articles. Descriptions of some key enablers are presented with examples from the source articles. The most significant enablers identified from the literature include digital fabrication engineers, parametric or computational resources, visual-programming condition, bespoke/customised design and modular attributes, digital fabrication optimisation and prefabrication processes, artefact of digital fabrication physical mockup, value of reducing human dependency, as well as risks of increasing uncertainty in production and performance compromise/uncertainty. Moreover, the authors conducted a frequency analysis to explore the frequency weights between any two enablers to understand how often they are mentioned together in literature. The frequency weights are presented in an adjacency matrix with the heat map visualisation. Key findings include many actor enablers are shown to have a strong relationship with processes and values, while condition enablers show a weak relationship with other enabler categories. In addition, the authors investigated the relational ontology networks of enablers through the lens of actor-network theory, which helps to discover the relationships between the enablers in networks and identify the significance in a hierarchy in regards to specific foci in design for digital fabrication. This work presents three network examples with circular construction focus, business model focus and digital twin in industrialisation focus. Each network is mapped in an onion diagram with all relevant enablers and their edges in-between based on literature. For example, prefabrication and modularisation processes are found to be significant to foster circular construction/design for disassembly in design for digital fabrication. Furthermore, this work presents the future methodology for process modelling in seven steps from the concept stage to the execution stage as an agile framework for stakeholders to develop a more beneficial construction process for an organisation. In conclusion, the limitations of this work and potential future research topics are described to extend this work in future research.

This work aims to foster digital fabrication adoption from its seed phase to a large-scale adoption in the design or planning phase. Also, this work assists project stakeholders to foster sustainable development for the economy, environment and society in the industry through adopting the emerging construction automation.

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.

Data availability

Data will be made available on request.

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