

# HOW PRODUCTIVE IS 3D CONCRETE PRINTING? A SYSTEMATIC REVIEW.

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## Abstract

3D concrete printing (3DCP) is considered a promising technology to digitise and transform the construction industry. The seamless design-to-fabrication workflow, the elimination of labour-intensive formwork and the general robotisation of construction are expected to significantly increase productivity in line with new architectural design possibilities. This paper presents the results of a systematic literature review summarising the productivity of 3DCP compared to conventional formwork-based construction. The identified and reviewed studies were categorised according to criteria for different levels of productivity. This includes categorisation by component and building level, and whether theoretical and empirical data has been collected on 3DCP or conventional processes. The results indicate that most studies evaluate labour productivity primarily based on empirical data from actual 3DCP, but do not always fully compare these to conventional construction. So far, productivity analysis was conducted at the component level and extrapolated to the building level. 3DCP offers cost and time savings of up to 79 % and 88 %, respectively, though some studies report increases of up to 50 % in cost and 16 % in time, pointing to the importance of context-specific factors. Many studies indicate the potential, which, however, are difficult to compare due to different levels of consideration. To be able to fully compare the results of the studies, many factors have to be standardised, such as different system boundaries, the degree of technological maturity and the selected printing parameters.

**Keywords:** Additive Manufacturing, Construction Industry, Digital fabrication, Labour productivity, Robotic Construction.

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## 1. Introduction

For decades, conventional concrete construction is primarily based on labour-intensive formwork, reinforcement and casting, almost without any fundamental changes over time. So far, the early rise of the industrialized construction as part of the Bauhaus movement in combination with the increasing rationalization of concrete construction, methods of systematisation and standardisation have been developed, which significantly changed the way we build [1]. However, it is almost astonishing that an economic sector contributing so significantly to the gross domestic product (GDP) has not experienced any notable increase in productivity in recent years. To be more precisely, the construction industry, which accounts for approximately 12% of the GDP in Germany, is actually facing a decline in productivity [2], [3]. This problem can be attributed to several structural and cultural factors within the sector. On the one hand, the construction industry is considered rather conservative. Its reluctance to adopt innovation originates mainly from the fragmented value chain and project-based collaboration [4]. On the other hand, the unique characteristics of the construction industry – such as site production, temporary production organization, one-of-a-kind products, and stringent safety and environmental regulations – further complicate the integration of new technologies [4]. As a result, while other sectors have embraced digital transformation and automation to boost efficiency, the construction industry continues to fall behind [5]. According to [5], the construction industry is one of the least digitalized industries in the world. While Building Information Modelling is one promising way of digitalizing the planning process,

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the execution remains mostly a labour-intensive manual task. To close the gap between digital planning and labour-intensive manual processes, digital fabrication (dfab) techniques, such as 3D concrete printing (3DCP) are considered as promising innovative technologies to boost the construction industry's productivity [6], [7]. 3DCP typically involves the pumping of premixed material through a nozzle, which is mounted on a gantry system or robotic arm, and extruding the material as thin layers (~6 mm to ~50 mm diameter) along a pre-determined path [8]. Significant efficiency gains are expected, particularly due to the closed digital process chain from planning to execution. Compared to conventional (formative) construction processes using formwork, 3DCP offers the advantage of eliminating labour-intensive formwork widely and enabling cost-effective customised fabrication through a direct, layer-by-layer, robot-controlled material application [7]. However, despite numerous research activities and the general promise of a higher productivity of 3DCP, a systematic overview is missing [9]. The systematic literature review presented here aims to investigate the underlying potential of 3DCP in terms of productivity and thereby to answer the question: How productive is 3DCP (really)?

Therefore, the paper is structured as follows: In section 2, the method to find the relevant research is explained in detail. In section 3, results and productivity potential based on the literature analysis are presented, which are then discussed in section 4. The paper is then concluded in section 5.

## 2. Method

Productivity (P) is commonly defined as the ratio between output (O), typically represented by the installed quantity (e.g. area of a concrete wall in square meter) and the input (I), expressed in terms of time or cost:  $P = O / I$ . Accordingly, a decrease in time or cost results an increase in productivity [6]. Therefore, a systematic literature review was conducted to identify relevant studies focussing both on productivity in time and cost. A structured search string was developed to ensure the retrieval of studies covering both the comparison between 3DCP and conventional construction methods, as well as productivity aspects. The specific search criteria applied in the final search are presented in Table 1.

Table 1. Search criteria for systematic literature review.

Category	Included terminology
<b>Building reference</b>	building, construction
<b>Technology reference</b>	additive manufacturing, additive construction, 3D print*, concrete print*, 3DCP, contour crafting, extrusion*, digital fabrication
<b>Comparison with conventional methods</b>	conventional, traditional
<b>Material</b>	concrete, cement, mortar
<b>Productivity</b>	productiv*, efficien*, economic, performance, time, cost, labour
<b>Comparison and evaluation methodology</b>	case study, evaluat*, compar*, examin*, analy*, empirical, simulat*, investigat*, practical, assessment
<b>Subject area LIMIT TO</b>	Engineering; Materials Science; Computer Science, Environmental Science; Business, Management and Accounting; Economics, Econometrics and Finance
<b>Document type LIMIT TO</b>	Article, Conference paper

The Scopus database was used for the search, which was performed in February 2025 and resulted in 343 records. A systematic, three-stage selection process based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines was applied to them [10]. First, titles and then abstracts were screened for specific relevance, followed by a detailed full-text reading, based on predefined exclusion criteria. Those studies were excluded that (1) showed a lack of comparability regarding productivity, (2) were not related to 3DCP or (3) were inaccessible. To minimise selection bias during the screening process, any unclear cases were identified and jointly reviewed by the authors, in accordance with PRISMA guidelines. In addition to the 15 studies identified by this systematic search, six further relevant studies were added using the snowball sampling method. This resulted in a final selection of 21 studies that were included in this review for further analysis of the productivity potential of 3DCP in comparison to conventional construction. The entire selection process is illustrated in the PRISMA flow diagram (see Fig. 1).

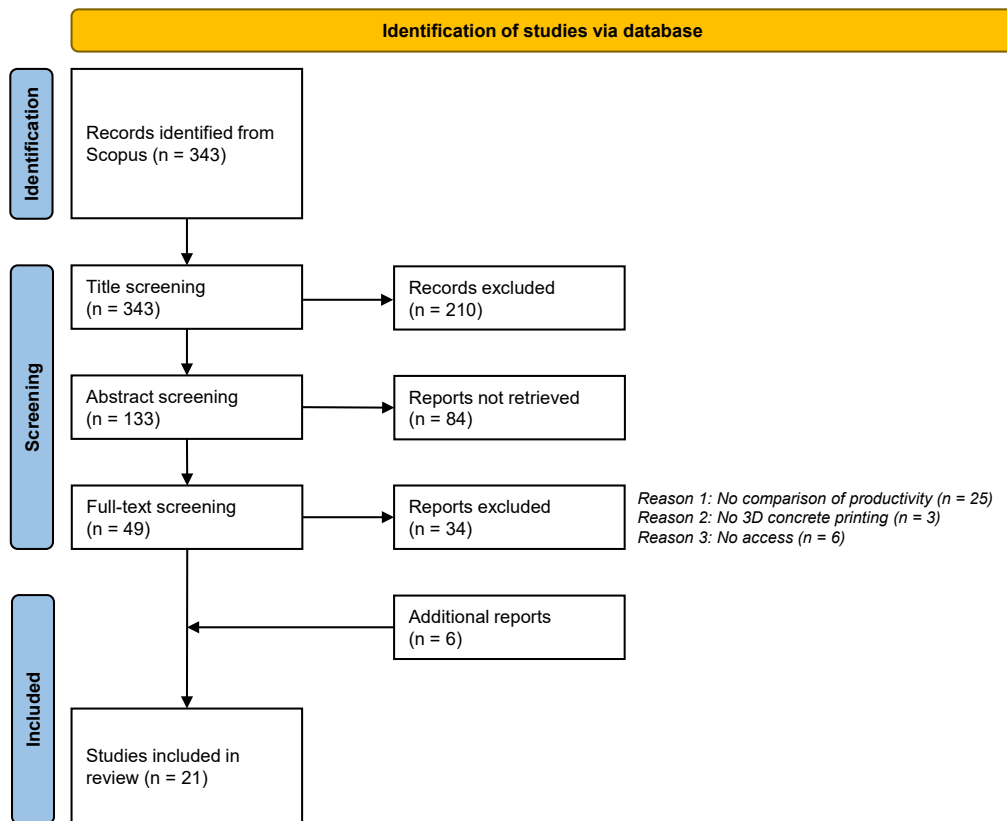


Fig. 1 PRISMA flow diagram summarizing the selection process from 343 records to 21 included studies.

### 3. Results

In this section, the 21 studies are analysed according to different categories, including scale of analysis, object of investigation, production strategy, type of data collection and type of productivity. This categorisation provides a structured overview of the general research focuses within the selected studies. A summary of these characteristics is presented in Table 2.

The objects of investigation vary significantly across the studies, which is reflected in three different scales: element, building and system. The majority of studies emphasize the element and building levels. The element level is focusing more on individual components such as single walls and columns, while the building level is analysing complete structures. However, the system level is addressed exclusively by [11] considering the entire construction process as a supply chain. Regarding production strategies, a fundamental distinction can be made between in-situ production and prefabrication for both 3DCP as preprinting and conventional construction methods as precast concrete. Most of the reviewed studies investigate in-situ 3D printing in comparison with cast-in-situ conventional construction. In terms of different data sources, an important distinction can be made between theoretical data (based on simulations or empirical estimates) and experimental data obtained through practical trials. Most studies rely either on theoretical data alone or on a combination of theoretical and experimental data. Only the studies by [12], [13], and [14] use experimental data for both 3DCP and conventional construction. The analysis of different types of productivity focuses primarily on cost-related and time-related productivity. While some studies examine both dimensions, others concentrate on one of the two aspects. Out of 21 studies, 17 compare the impact of 3DCP to productivity in terms of time and 13 to productivity in terms of cost. In addition, the study by [11] introduces cumulative effort as an additional productivity indicator, referring to the total resources required to complete a construction project successfully. Building on this structured overview, the following sections provide a detailed summary of the reported productivity potentials, focusing separately on time and costs.

Table 2. Overview of the included studies and their research focus on productivity aspects of 3DCP

Authors	Year	Scale	Object of investigation	Production strategy		Data collection		Type of productivity	Ref.
				3DCP	Conventional	3DCP	Conventional		
Forcael et al.	2023	building	2-floor and 12-floor building	in-situ	cast-in-situ	theoretically	theoretically	time	[15]
Ayyagari et al.	2023	system	2-floor office building	in-situ	cast-in-situ	theoretically	theoretically	time, cumulative effort	[11]
Alabbasi et al.	2023	element	concrete column	preprinting	N/A	experimental	theoretically	time	[16]
Oktaviani & Berawi	2022	element	precast beam panels	preprinting	precast	theoretically	experimental	time	[17]
Xu et al.	2022	building	farmhouse in Wujiazhuang (WJZ)	in-situ	cast-in-situ	experimental	theoretically	time	[18]
Abdalla et al.	2021	building	single-storey house in UAE	in-situ	cast-in-situ	experimental	experimental	time, cost	[12]
Han et al.	2021	building	concrete silo, single-stair concrete bungalow	in-situ	cast-in-situ	theoretically	theoretically	cost	[19]
Khajavi et al.	2021	building	2 urban residential buildings (round, rectangular)	in-situ, preprinting	cast-in-situ, precast	theoretically	theoretically	time, cost	[20]
Pekuss et al.	2021	element	10 pillars with varying complexity	in-situ	cast-in-situ, precast	theoretically	theoretically	time	[21]
Ul Fazal & Batikha	2021	building	6 unit two-storey townhouse building	in-situ	precast	theoretically	experimental	time, cost	[22]
Abou Yassin et al.	2020	building	retaining and shear walls	in-situ	cast-in-situ	theoretically	theoretically	time, cost	[23]
Jagoda et al.	2020	element	concrete dragon's teeth	in-situ	cast-in-situ	experimental	theoretically	time, cost	[24]
Otto et al.	2020	building	4 wall types	in-situ	cast-in-situ, masonry construction	experimental	theoretically	time, cost	[25]
Pekuss & Garcia de Soto	2020	element	concrete column with a simple geometry	preprinting	cast-in-situ, precast	experimental	theoretically	time, cost	[26]
Weng et al.	2020	element	cubic bathroom unit	in-situ	precast	experimental	experimental	time, cost	[13]
Allouzi et al.	2020	building	Ras Alain Multipurpose Hall	in-situ	cast-in-situ, masonry construction	theoretically	experimental	cost	[27]
Kreiger et al.	2019	building	B-Hut A and B-Hut B	in-situ	cast-in-situ, masonry construction	experimental	theoretically	cost	[28]
A. L. M. Tobi et al.	2018	building	house	in-situ	N/A	theoretically	theoretically	cost	[29]
El Sakka & Hamzeh	2017	element	walls	in-situ	masonry construction	experimental	experimental	time	[14]
Rouhana et al.	2014	building	200 m <sup>2</sup> building	in-situ	cast-in-situ	theoretically	theoretically	time	[30]
Bossher et al.	2007	element	foundation wall	in-situ	cast-in-situ	theoretically	theoretically	time, cost	[31]

N/A = not available

### 3.1. Productivity in terms of time

The systematic summary of the productivity in terms of time impacts of 3DCP in comparison to conventional construction methods is presented in Table 3. It also displays the observed savings or additional efforts as percentages, linked to specific time or cost categories. When multiple scenarios are analysed, relevant contextual parameters are then specified in the accompanying notes.

Table 3. Summary of reported productivity potentials of 3DCP in terms of time.

Authors	Year	Productivity potential of 3DCP ( <i>in comparison to conventional construction method</i> )		Notes	Ref.
		Time (saving ↓ ↑ additional effort)			
Forcael et al.	2023	45 % ↓	construction time	small building	[15]
		40 % ↑	construction time	big building (1 robot)	
		80 % ↓	construction time	big building (3 robots)	
Ayyagari et al.	2023	6 % ↓	production rate	3DP-CSC	[11]
		6 % ↑	production rate	P3DP-CSC	
Alabbasi et al.	2023	50 % ↓	construction time		[16]
		38 % ↓	man-hours		
Oktaviani/Berawi	2022	50 % ↑	production rate	3DCP as SIP-formwork	[17]
Xu et al.	2022	28 % ↓	man-hours	common 3DCP	[18]
		62 % ↓	man-hours	3D-Print-Workflow	
Abdalla et al.	2021	88 % ↓	construction time		[12]
Khajavi et al.	2021	85 % ↓	construction time	round building (in-situ)	[20]
		85 % ↓	construction time	rectangular building (in-situ)	
Pekuss et al.	2021	9 % ↑	construction time	simple geometries - cast-in-situ	[21]
		16 % ↑	construction time	simple geometries - precast	
		38 % ↓	construction time	complex geometries - cast-in-situ	
		42 % ↓	construction time	complex geometries - precast	
Ul Fazal/Batikha	2021	34 % ↓	man-hours		[22]
Abou Yassin et al.	2020	60 % ↓	construction time		[23]
Jagoda et al.	2020	61 - 84 % ↓	construction time		[24]
Otto et al.	2020	72 % ↓	construction time	unreinforced cast-in-situ concrete wall	[25]
		67 % ↓	construction time	clay masonry wall	
		46 % ↓	construction time	sand-lime masonry wall	
Pekuss/García de Soto	2020	13 - 19 % ↓	productivity <sup>1</sup> incl. curing,transport	3DCP as SIP-formwork vs. cast-in-situ	[26]
		7 - 12 % ↓	productivity <sup>1</sup> incl. curing,transport	3DCP as SIP-formwork vs. precast	
		1003-1097 % ↓	productivity <sup>1</sup> excl. curing,transport	3DCP as SIP-formwork vs. cast-in-situ	
		1247-1365 % ↓	productivity <sup>1</sup> excl. curing,transport	3DCP as SIP-formwork vs. Precast	
Weng et al.	2020	48 % ↑	labour productivity		[13]
El Sakka/Hamzeh	2017	60 % ↓	construction time		[14]
Rouhana et al.	2014	67 % ↓	construction time		[30]
Bosscher et al.	2007	27 % ↑	labour productivity	per 8-hour working day	[31]

<sup>1</sup> A lower productivity means additional effort in time and vice versa.

Looking more closely at the studies reviewed, a more precise differentiation can even be found between different categories of time. 'Construction time' refers to the execution time required to complete a construction project, excluding any planning efforts. It represents the primary reference time in the present analysis and is applied in 10 of the reviewed studies, as seen in Table 3. Six studies focus on man-hours or labour productivity, both therefore relating to the workers effort performed. Additionally, two studies use the production rate as a reference value, which describes the amount of construction output, such as volume or area, completed within a specific period. The detailed analysis reveals a trend at first sight: 13 studies report that the use of 3DCP is associated with a reduction in time, ranging from

6 % to 88 %. However, the studies by [11], [15], [21], [26] indicate a different picture. In the cases of [15], [21], [26], the outcome depends more on specific parameters such as geometry, production strategy or number of robots used, leading to either time savings or increased construction times for 3DCP. Notably, the study by [26] reports a significant decline in productivity, with construction times between 7 % and 1365 % longer than those observed with conventional construction methods.

Furthermore, in the evaluation of geometric complexity effects on 3DCP productivity on element level, simple circular columns produced by 3DCP required 9 % more time than cast-in-situ and 16 % more time than precast concrete counterparts [26]. When geometric complexity increases, 3DCP outperforms conventional methods [26]. With low complexity, 3DCP was up to 8.9 % slower than cast-in-situ and up to 16.7 % slower than precast; in the case of high complexity, 3DCP achieved maximum productivity gains of 37.9 % over cast-in-situ and 41.9 % over precast methods. The same authors quantified this trend in another study using a complexity-weighted build-time factor for columns [21]. In contrast and on building level, [20] found that a circular and rectangular building print each achieved 85 % construction time savings compared to conventional methods, irrespective of form.

[15] report that building size significantly influences the achievable time savings in 3DCP. For smaller buildings, such as a single-storey house, time savings of 45 % can be realised. For larger buildings, in contrast, like a twelve-storey high-rise, 3DCP leads to a 40 % increase in construction time compared to conventional methods. Increasing the number of robots from one to three can mitigate this drawback, ultimately achieving a time reduction of up to 80 %.

In addition, table 3 indicates a dependency between the chosen production strategy and the resulting productivity potential in terms of time. The results reported by [26] are particularly notable: The authors of this study used a three-folded approach, calculating pessimistic, most-likely and optimistic values. The use of 3DCP as stay-in-place (SIP) formwork reduced the productivity by 7 % to 19 %, when transport and curing times are considered. Excluding these factors, the productivity was reduced by as much as 1003 % to 1365 %.

Both [18] and [11] incorporate future scenarios by comparing conventional construction with current and optimised 3DCP workflows. According to [18], common 3DCP, where only the walls are printed and other components such as foundations and slabs are conventionally produced, already yields a 28 % reduction in man-hours. This potential could increase to 62 % when applying a full 3D-printed workflow, where all components are printed. In a more comprehensive view of the whole construction supply chain on system level, [11] analysed current 3D printing (3DP-CSC) and projected optimistic 3D printing (P3DP-CSC) compared to conventional construction. While the current 3DCP-CSC use may still result in a 6 % lower production rate, the P3DP-CSC scenario anticipates a 6 % increase in production rate.

### *3.2. Productivity in terms of cost*

Table 4 gives an overview of the productivity in terms of cost associated with 3DCP in comparison to conventional construction. The structure corresponds to Table 3. It can be seen that the studies differentiate between different types of costs: Construction costs refer to the costs associated with the execution phase of a project, including labour, material, and equipment. Essentially, the construction costs are considered in the studies. Sometimes, transport or curing costs are additionally considered, like in [20] or [26]. Moreover, only the study by [26] undertakes a direct evaluation of productivity based on construction costs, instead of comparing the costs itself. In the paper of [22], [23], [24], the effect of specific boundary conditions such as geometry or production strategy is considered, leading to higher or lower costs.

Compared to productivity in terms of time, the trend regarding cost savings seems similar, but is more differentiated. Across the reviewed studies, a reduction in costs is reported in nine cases, whereas an increase in costs is once again identified by [26]. Generally, it seems that 3DCP offers higher potential at building level than at element level: The productivity potential, however, varies greatly in the studies by [19], [20], [25], [27], [28]. While [28] estimate 10-25 % cost savings compared to masonry construction, they indicate even higher saving of 25-37 % when compared to cast-in-situ. However, the geometric complexity of the ground floor seems to have an impact as well: [19] claims productivity

potential in terms of cost ranging from 17 % for rectangular buildings up to 79 % for round buildings. However, [20] reports a more moderate advantage of 45 % (rectangular) to 58 % (round) for 3DCP.

Table 4. Summary of reported productivity potentials of 3DCP in terms of costs.

Authors	Year	Productivity potential of 3DCP ( <i>in comparison to conventional construction method</i> )		Notes	Ref.
		Cost (saving ↓ ↑ additional effort)			
Ayyagari et al.	2023	21 % ↑	cumulative effort <sup>1</sup>	3DP-CSC	[11]
		7 % ↑	cumulative effort <sup>1</sup>	P3DP-CSC	
Abdalla et al.	2021	78 % ↓	labour and material costs		[12]
Han et al.	2021	79 % ↓	construction costs	round building	[19]
		17 % ↓	construction costs	rectangular building	
Khajavi et al.	2021	58 % ↓	construction and transport costs	round building (in-situ)	[20]
		45 % ↓	construction and transport costs	rectangular building (in-situ)	
Ul Fazal/Batikha	2021	5 % ↑	construction costs		[22]
		11 % ↓	equipment and labour costs		
		44 % ↑	material costs		
Abou Yassin et al.	2020	↑ ↓	equipment and labour costs	break-even-point: time > 6 months	[23]
Jagoda et al.	2020	50 % ↑	construction costs		[24]
		70 % ↓	labour costs		
		472 % ↑	material costs		
Otto et al.	2020	39 % ↓	construction costs	unreinforced cast-in-situ wall	[25]
		5 % ↓	construction costs	clay masonry wall	
		3 % ↓	construction costs	sand-lime masonry wall	
Pekuss/García de Soto	2020	73 - 160 % ↓	productivity <sup>2</sup> incl. curing, transport	3DCP as SIP-formwork vs. cast-in-situ	[26]
		65 - 148 % ↓	productivity <sup>2</sup> incl. curing, transport	3DCP as SIP-formwork vs. precast	
		48 - 136 % ↓	productivity <sup>2</sup> excl. curing, transport	3DCP as SIP-formwork vs. cast-in-situ	
		85 - 194 % ↓	productivity <sup>2</sup> excl. curing, transport	3DCP as SIP-formwork vs. precast	
Weng et al.	2020	25 % ↓	construction costs		[13]
		14 % ↓	labour costs		
Allouzi et al.	2020	65 % ↓	material costs		[27]
Kreiger et al.	2019	10 - 25 % ↓	construction costs	masonry construction	[28]
		25 - 37 % ↓	construction costs	cast-in-situ	
A. L. M. Tobi et al.	2018	30 % ↓	total house price		[29]
Bosscher et al.	2007	3 % ↓	equipment and labour costs		[31]

<sup>1</sup> refers to the required resources to complete a construction and not explicitly to costs

<sup>2</sup> A lower productivity means additional effort in costs and vice versa.

According to [12], [13], [22], [23], [24], [31], the labour costs will be reduced due to the automated printing process. However, [11], [22], [24] indicate that the decreased labour costs correlates with an increase in material costs when 3DCP is applied. As reported in [22] and [24], this caused an 5 % and an 50 % increase in construction costs. The assessment of equipment costs for 3D Printers, such as gantry systems or robotic arms, remains difficult. Due to the high equipment costs, [23] determines a break-even-point for 3DCP after six months compared to conventional cast-in-situ. Similarly, [25] considers the cost of the 3D printer to be unknown and defines the cost differences in comparison to other processes, such as the cost budget for the 3D printer. Compared to a conventional, cast-in-situ unreinforced concrete wall, 3DCP can save up to 72 % of construction costs (in total) [25]. [11] introduced a different perspective and focussed on cumulative effort, examining the total resources required to complete a construction project successfully. In the current 3DP-CSC setup, an additional effort of 21 % is needed. However, this could be reduced to 7 % (P3DP-CSC).

## 4. Discussion

Within this section, the challenges in comparing productivity, the reliability of the reported findings as well as the limitations of the reviewed studies are discussed.

### 4.1. Challenges in comparing productivity

A fundamental challenge while comparing productivity potentials between the reviewed studies is the limited matching of their detailed results. This limitation is primarily caused by the consideration of different objects and their transparent plus well-documented data sampling. Additionally, the evaluation of productivity potential is based on various assumptions and boundary conditions, which limits the comparability of reported savings further. The following aspects should therefore be considered:

- Production Strategy: cast-in-situ or prefabrication vs. in-situ-printing or preprinting
- System level: system (supply chain), building or element
- Boundaries conditions: construction process incl. or excl. design process (and effort)
- Object of investigation: wall, column, foundations, ...
- Comparable construction methods: masonry construction, cast-in-situ construction, ...
- Architectural or building design of compared object: architectural features, such as wall interior design; Building form, such as round or rectangular and geometric complexity
- Data sampling: empirical data vs. theoretical data
- Reference of productivity in terms of time: labour productivity (man-hours) or construction time
- Reference of productivity in terms of cost: equipment, labour or material costs

### 4.2. Limitations and outlook

A central limitation of the reviewed studies is their narrow focus on the execution phase of construction. Except for [11], planning efforts are either neglected or only marginally addressed. This may lead to a false interpretation of the reported productivity gains, particularly if the initial planning effort for 3DCP is higher than for conventional methods. Future research should prioritise repeated empirical trials over single case analyses or theoretical simulations when comparing the performance of 3DCP with conventional methods.

## 5. Conclusion

In this paper, a systematic literature review revealed that 3DCP shows promising potential for improving productivity in construction. While many studies report cost savings ranging from 10 % to 79 % and time savings from 6 % to 88 % for 3DCP, not all findings are consistent. Some studies indicated increased costs of up to 50 % or additional construction time of up to 16%, indicating that a more differentiated analysis is needed, considering factors such as geometry, building size, production strategy, and cost allocation. It needs to be stated that the productivity potential of 3DCP cannot be reduced to a single, fixed number. For future comparisons, there is a strong need for standardised benchmarking framework that combines the added value of increased geometric complexity with the economic potential.

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