3D Printing vs. Traditional Construction: Cost Comparisons from Design to Waste Disposal Stages

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Abstract –

Construction 3D printing (3DP) has the potential to be cost-effective compared to traditional construction, due to its shorter supply chain and higher level of automation. However, there is a lack of comprehensive studies comparing the costs of traditional construction and 3DP across various stages, from design to waste disposal. Therefore, this study investigates the overall cost of traditional and 3DP construction, considering both off-site and on-site 3DP techniques. Mathematical models are developed to analyse costs, including research and development (R&D), Architecture, Engineering, and Construction (AEC), transportation, warehousing, setup installation, printing and on-site assembling processes, waste disposal, and environmental costs. Real-time case studies have been investigated to validate the feasibility and practicality of the models. The comparative analysis revealed that the design stage cost of 3DP is 19 times higher than those of traditional construction due to significant investments in R&D. Off-site 3DP incurs higher logistics costs primarily due to holding costs. Nevertheless, it becomes a more viable option for small-scale projects (less than 35t for the considered cases), like printing architectural elements, as the expense of delivering printed components to the construction site is lower compared to transporting bulky 3DP equipment and raw materials. On-site 3DP presents a competitive alternative to traditional construction methods, both for individual projects and large-scale developments. The findings of this research provide valuable insights that can help the construction industry optimize cost-effectiveness and enhance efficiency in construction practices.

Keywords –

3D printing, logistics, economic assessment, additive manufacturing, case study

1 Introduction

The fourth industrial revolution, known as Industry 4.0, is characterized by the digitization of complex industrial tasks. One of the key technological advancements driving this digital transformation is 3DP, also referred to as additive manufacturing or rapid manufacturing [1]. 3DP involves the layer-by-layer joining of materials to create objects based on three-dimensional models [2]. The global 3DP market experienced significant growth in 2020, with a remarkable 21% increase compared to 2019, reaching an estimated value of $12.6 billion [3]. This growth highlights the potential of 3DP technology to drive various industries towards digitalization. In the construction industry, 3DP technology shows great promise in reducing labor costs, construction time, risky human operations, material usage, and waste [4, 5]. Additionally, it offers the advantage of architectural design flexibility and provides social and environmental benefits [6]. Consequently, significant efforts have been made by stakeholders to advance the construction 3DP industry. These efforts include the development of 3D printer robotic systems, suitable printed materials, and new applications. Various organizations worldwide have completed numerous single projects, ranging from small-scale structures to entire low-rise buildings. However, 3DP has yet to be thoroughly tested in mass-production scenarios [7, 8].

Despite growing interest and knowledge in 3DP technologies, their adoption in the construction industry lags behind the manufacturing sector [9]. Challenges such as technological feasibility, cost and time benefits, user training, safety considerations, and compliance with contractual and standard requirements impede widespread adoption [10]. These concerns create doubts among potential adopters about the value of implementing 3DP technology [11].

Several research studies have focused on the economic analysis of construction 3DP. Tobi, et al. [12] found that 3DP has the potential to reduce construction costs by 30% compared to conventional techniques. Yang, et al. [13] developed a cost calculation method considering various factors such as labor, material, machine, management, safety, and environmental costs for both off-site and on-site 3D printing. Aghimien, et al. [14] gathered insights from construction industry professionals and demonstrated that construction 3DP offers improved cost efficiency in housing projects and enhances productivity. Weng, et al. [15] conducted a comparative economic analysis of 3D concrete printing and precasting, observing a 34% reduction in overall costs for 3DP construction. Allouzi, et al. [16] compared 3DP with conventional construction techniques for a single-story building, finding a 65% reduction in material costs for 3DP. Markin, et al. [17] estimated the cost of foam concrete exterior walls produced through 3DP, with material costs contributing 70% to the total direct cost. Han, et al. [18] conducted a comparative analysis of 3DP and conventional construction methods for a hypothetical cylindrical silo, highlighting that material costs accounted for 83% of the overall cost in 3DP. Abdalla, et al. [19] compared the costs of formwork and raw materials between construction 3DP and conventional construction, reporting a 78% lower capital cost for 3DP due to the absence of formwork and concrete. The above-mentioned studies discuss various cost components related to the construction phase, with some addressing environmental factors during the construction stage and resource utilization. Besklubova, et al. [20] conducted a detailed analysis of logistics costs for construction 3DP of low-story buildings, covering the entire process from suppliers to waste disposal.

While various studies have focused on cost analysis in construction 3DP, they often consider specific stages such as construction or logistics individually. As a result, obtaining a comprehensive understanding of the cost structure for the entire 3DP project, from design to waste disposal, continues to be a challenge. To address this gap, the current study provides a comprehensive cost analysis throughout the entire process, including environmental factors. This study considers two different 3DP construction techniques including off-site and on-site 3DP, to comprehensively assess their cost-effectiveness.

2 Model development

The research methodology consists of four key steps. Firstly, a comprehensive literature review was conducted. This literature review provided insights into the processes involved in each stage of construction projects and established a theoretical foundation for developing a cost estimation model to assess construction projects from the design to realization stage.

Secondly, the development of the cost estimation model began by selecting parameters based on the involved processes. The parameter selection followed the Activity-Based Costing (ABC) approach, which aims to accurately allocate overhead costs and resources, such as labor, materials, and equipment costs, to processes based on their actual consumption of resources. In comparison to traditional cost analysis approaches (uses machine hours or man-hours consumed as the basis for estimating costs), ABC method provides more accurate cost information, which enables effective monitoring of supply chain and production strategies [21]. Subsequently, the model assumptions were defined, and the parameters were quantified and formulated.

Thirdly, three comparable case studies were selected to ensure the feasibility and practicality of the proposed model. These case studies represented on-site 3DP, off-site 3DP, and traditional construction. A three-step data collection approach was utilized to gather a comprehensive dataset, employing triangulation of evidence from three interrelated methods [22].

Finally, a comprehensive cost breakdown analysis was carried out to evaluate and understand the individual cost components associated with both 3DP and traditional construction processes. Additionally, a sensitivity analysis was conducted for critical cost components, followed by data processing. Sensitivity analysis involves examining how uncertainty in model output, whether numerical or otherwise, can be attributed to various sources of uncertainty in the model input.

2.1 Parameters selection

The low-rise building project process involves different stages, including the design stage, logistics, and construction process (printing and assembly). The design stage includes R&D and AEC activities. In the traditional construction supply chain (CSC) flow, raw materials are obtained from suppliers and processed by manufacturers to create construction materials and elements. These materials and elements are then transported to the construction site, and any waste generated during the construction process is transported to disposal facilities (Figure1 (a)) [4, 23]. In the case of construction 3DP technology, there are two main supply chain configurations: on-site and off-site [4, 24]. On-site printing involves moving raw materials and 3DP equipment directly to the construction site (Figure1 (b)). Although 3DP is often touted as a zero-waste technology [25], waste disposal facilities are still a part of the supply chain at its current stage of development. This is because the technology, with its imperfections such as failed components and inaccurate material calculation, still generates waste during the printing process [4]. Off-site printing involves moving materials from suppliers to a

3DP manufactory facility, and then to the construction site for assembly (Figure 1(c)). Similar to the above, construction waste is transported to disposal facilities. The logistics cost components have been discussed in detail by Besklubova, et al. [20]. Construction process costs encompass materials, machinery, equipment, and environmental factors.

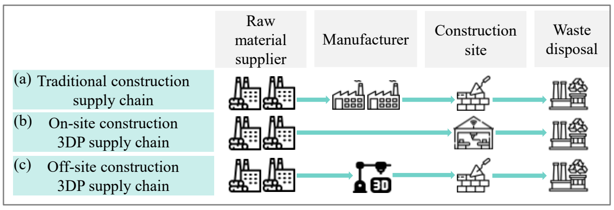

Figure 1. Construction supply chain configurations for small and medium scale projects: (a) traditional, (b) on-site 3DP, and (c) off-site 3DP

2.2 Model assumptions

The model assumes a unidirectional flow, specifically from the supplier of raw materials to the off-site manufacturing facility, then from the manufacturing facility to the warehouse, and finally from the warehouse to the construction site and then to disposal facilities. In the case of off-site 3DP, there is no need to transport equipment because the 3DP equipment is owned by the off-site manufacturer. There is no limit to the total number of facilities at each node. To estimate the distances between the facilities, Google Maps is utilized [26]. The labour wage rates used in the analysis are based on the latest standard rates obtained from reliable online sources. The printing process considers the times required for installation, printer setup, material preparation, and actual walls printing. The 3DP equipment consists of a 3D printer, batching plant, concrete piston pump, and concrete silo. In the case of off-site 3DP, a crane is also utilized for the assembly of printed components. It should be noted that the development of the pricing policy did not consider weather conditions.

2.3 Quantification of parameters

This section explains how to quantify the total construction project cost and its related cost components. The activities involved in each construction stage were assessed using the ABC approach. The cost component parameters are summarized in Table 1 and expressed via equations 1-4 below.

Table 1. List of parameters

Parameters	Description
n^{rd}	Manpower for R&D
n^{ds}	Manpower at design stage
w^{rd}	Average salary for R&D
w^{ds}	Average architect's salary
t^{rd}/t^{ds}	Project preparation period (R&D/ design)
HC_i^{mat}	Handling cost per unit of material at facility i
IHC_i^{mat} IHC_i^{comp}	Inventory holding cost per unit of materials/printed components at facility i
DC_i^{waste}	Disposal cost per unit of waste
TC_{ij}	Transportation cost from i to j, $i \neq j$
Q_i^{mat}	Quantities of materials at facility i
Q_{ij}^{mat}	Quantities of materials transported from i to j, $i \neq j$
V_{ij}^{eq}	Volume of equipment transported from i to j, $i \neq j$
SUt_i^{eq}	Time required for each set up of the 3D printer at facility i
SUn_i^{eq}	Number of the 3D printer set up times at facility i
E_{ij}	Carbon emissions factor for diesel consumption for material/ equipment transportation from i to j, $i \neq j$
CE_{CO_2}	Environmental cost of CO_2 emissions
dis_{ij}^{mat}	Distance from i to j for material supply, $i \neq j$
dis_{ij}^{eq}	Distance from i to j for equipment supply, $i \neq j$
n_i^{SU}	Number of workers for equipment set up at facility i
w_i^{SU}	Construction site worker wage rate for equipment set up at facility i
n_{ij}^{truck}	Number of 18 tonnes-trucks for materials transportation from i to j, $i \neq j$
n_{ij}^{cont}	Number of 20-foot 3D printer transport containers from i to j, $i \neq j$
t_{hold}^{mat} t_{hold}^{comp}	Holding time of materials/printed components
t^c	Time required for construction
w^c	Average salary for construction workers
n^c	Manpower at construction stage
MC	Cost of one tonne of material
EqC_i	Equipment cost (3D printing equipment and crane) i, $i = 1 \dots I$
EC	Unit energy cost
t_i^{eq}	Time for the equipment operation i, $i = 1 \dots I$ during 3DP/assembly

PC_i	Power capacity (kW) of equipment i, $i = 1 \dots I$
EL_i	Useful life of equipment i, $i = 1 \dots I$
FC	Unit fuel (diesel) cost per liter
$FCon_i$	Fuel consumption factor for diesel machinery (e.g., crane) per hour i, $i = 1 \dots I$
E_i^{el}	Carbon emissions factor for electrical equipment i, $i = 1 \dots I$
E_i^{dis}	Carbon emissions factor for diesel machinery i, $i = 1 \dots I$

$$\text{TotalCost} = \text{Project preparation cost} + \text{Logistics cost} + \text{Construction cost} \tag{1}$$

$$\text{Project preparation cost} = \begin{bmatrix} \textit{Research and Development} + \\ \textit{Project Design} \end{bmatrix} = \begin{cases} n^{rd} \times t^{rd} \times w^{rd} \\ + \\ n^{ds} \times t^{ds} \times w^{ds} \end{cases} \tag{2}$$

$$\text{Logistics cost} = \begin{bmatrix} \text{HandlingCost}^{\text{mat}} + \\ \text{HoldingCost}^{\text{mat}} + \\ \text{DisposalCost}^{\text{waste}} + \\ \text{SetUpCost}^{\text{eq}} + \\ \text{TransportationCost} + \\ \text{EnvironmentalCost} + \end{bmatrix} = \begin{cases} \sum_{i=1}^{I} \text{HC}_i^{\text{mat}} \times \text{Q}_i^{\text{mat}} + \\ \begin{bmatrix} \sum_{i=1}^{I} \text{IHC}_i^{\text{mat}} \times \text{Q}_i^{\text{mat}} \times \text{t}_{\text{hold}}^{\text{mat}} + \\ \sum_{i=1}^{I} \text{IHC}_i^{comp} \times \text{Q}_i^{\text{mat}} \times \text{t}_{\text{hold}}^{\text{comp}} \end{bmatrix} + \\ \sum_{i=1}^{I}\sum_{j=1}^{J} \text{DC}_i^{\text{waste}} \times \text{Q}_{ij}^{\text{mat}} + \\ \sum_{i=1}^{I} \text{SUt}_i^{\text{eq}} \times \text{SUn}_i^{\text{eq}} \times \text{n}_i^{\text{SU}} \times \text{w}_i^{\text{SU}} + \\ \begin{bmatrix} \sum_{i=1}^{I}\sum_{j=1}^{J} \text{TC}_{ij} \times \text{n}_{ij}^{\text{truck}} \times \text{dis}_{ij}^{\text{mat}} + \\ \sum_{i=1}^{I}\sum_{j=1}^{J} \text{TC}_{ij} \times \text{n}_{ij}^{\text{cont}} \times \text{dis}_{ij}^{\text{eq}} \end{bmatrix} + \\ \left[\left(\begin{matrix} \sum_{i=1}^{I}\sum_{j=1}^{J} \text{E}_{ij} \times \text{n}_{ij}^{\text{truck}} \times \text{dist}_{ij}^{\text{mat}} + \\ \sum_{i=1}^{I}\sum_{j=1}^{J} \text{E}_{ij} \times \text{n}_{ij}^{\text{cont}} \times \text{dist}_{ij}^{\text{eq}} \end{matrix}\right) \times \text{CE}_{\text{CO}_2}\right] \end{cases} \tag{3}$$

$$\text{Construction cost} = \begin{bmatrix} \textit{Labour cost} + \\ \textit{Material cost} + \\ \textit{Equipment cost} + \\ \textit{EnergyConsumption} + \\ \textit{Environmental cost (constr)} \end{bmatrix} = \begin{cases} t^c \times w^c \times n^c + \\ \text{MC} \times Q_i^{mat} + \\ \sum_{i=1}^{I} \frac{\text{EqC}_i}{EL_i} \times t_i^{eq} + \\ \begin{bmatrix} \sum_{i=1}^{I} EC \times t_i^{eq} \times PC_i + \\ \sum_{i=1}^{I} FC \times t_i^{eq} \times FCon_i \end{bmatrix} + \\ \left[\left(\begin{matrix} \sum_{i=1}^{I} E_i^{el} \times t_i^{eq} \times PC_i + \\ \sum_{i=1}^{I} E_i^{dis} \times t_i^{eq} \times FCon_i \end{matrix}\right) \times CE_{CO_2}\right] \end{cases} \tag{4}$$

3 Case study

This section illustrates the implementation of the proposed model to evaluate the feasibility of 3D printed projects compared to traditional construction methods. Case studies of residential buildings in Berlin and Beckum (Germany) are selected. The on-site 3D printed project, a collaborative effort involving PERI, COBOD, etc., was chosen due to its non-standard shape and on-site construction, aligning with industry interests. The project holds a building permit from the office in Beckum, providing valuable insights. The data from this project is sufficient for the case of 3DP off-site. A traditionally constructed house in Berlin, which utilized sand-lime blocks and had a similar floor area, was chosen for the comparison. These projects meet the selection criteria for the case study [27] because they are real examples from the same country, with similar currency, and quantum of work, and provide comprehensive data on various aspects. Even though the projects were implemented in different-sized cities (Berlin and Beckum), the cost calculations were based on average values for Germany. This includes factors such as material, equipment, and waste transportation, which often involve intercity logistics.

3.1 Data collection

To obtain a comprehensive set of data, a three-step data collection approach was employed [22]. The approach includes gathering data from open-source documents and articles, conducting surveys using a survey form, and conducting open-question interviews. The 3DP cases in this study utilized the BOD2 concrete printer, which was purchased by PERI. This printer model consists of a gantry system with multiple modules, enabling its use for both on-site concrete projects and off-site element production. The gathered data was then prepared for use in the model, which involved matching the obtained data with the parameters in the model.

3.2 Data processing

The prepared data is utilized in the model to calculate the different cost components. The cost of the project design and preparation stage is determined using Eq. (2), logistics cost is calculated using Eq. (3), and the construction cost is derived from Eq. (4). The calculated costs are summarized in Table 2. A pie chart is drawn to visualize the percentage of each cost component within the total cost for each case (Figure 2). Three cost elements (holding, set up, and construction environmental costs) are not included in the pie chart legend as their contribution to the total cost is negligible, close to or equal to zero.

The total cost for traditional construction amounts to €93,480, while on-site 3DP reaches €418,489 and off-site 3DP reaches €472,581. Upon conducting a comparative analysis, it becomes evident that approximately 80% and 71% of the total costs are attributed to the project preparation stage, which involves R&D. During this stage of construction 3DP development, each project is treated as unique and requires extensive preparation from the initial phase. Additionally, the active development of 3DP equipment necessitates significant investments in software and hardware updates for each project. However, as the technology matures and becomes more widely used, project designs can be applied to multiple housing projects using the same 3DP equipment, making the project preparation stage comparable to that of traditional construction. For example, establish a library of reusable designs from which the chosen project can be downloaded [28]. The logistic cost for off-site 3DP is higher due to the additional transportation of prefabricated components. On the other hand, on-site 3DP has a higher cost compared to traditional construction due to the transportation of massive 3DP equipment. However, more compact 3D printing robotic solutions are available in the market for use [20]. Moreover, despite the lower amount of materials involved, the material transportation costs of on-site 3DP are higher compared to traditional construction. This observation indicates that despite claims of traditional construction materials, such as cement, being suitable for 3DP technology [7], companies often procure materials from specialized 3DP organizations (e.g., equipment vendors often serve as the suppliers of raw materials) instead of purchasing them from the nearest convenient company [29]. Previous studies have also highlighted the insufficiency of printing materials (e.g., Hossain, et al. [4], Zhang, et al. [30]).

In terms of construction cost, it accounts for approximately 7%, 10%, and 70% of the total cost in the cases of on-site 3DP, off-site 3DP, and traditional construction, respectively. Specifically, the construction cost of traditionally built projects is approximately 2.5 times higher than that of on-site 3DP construction due to its longer duration, which requires more manpower usage.

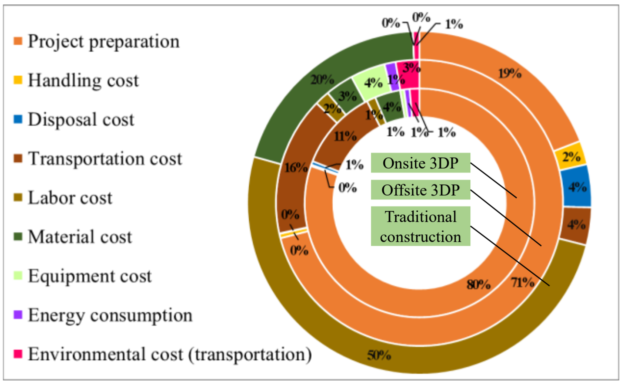

Figure 2. Cost profile for three scenarios

Table 2. Costs calculation

Cost components	3DP on-site, €	3DP off-site, €	Traditional construction,€
Project preparation	*335 000 (80%)*	*335 000 (71%)*	*17 866,7 (19%)*
Handling cost	852.6	2305.2	2091.6
Holding cost	91.8	248.4	91.8
Disposal cost	2121.2	284.1	3787.9
Set up cost	576.0	0.0	0.0
Transport. cost	47998.9	74028.5	3329.1
Environmental cost(transport.)	5717.0	12596.2	568.1
Logistics cost	*57357.4 (13%)*	*89462.5 (19%)*	*9868.5 (11%)*
Labor cost	5280.0	7892.5	47025.0
Material cost	14976.0	15050.9	18720.0
Equipment cost	2400.0	18550.0	0.0
Energy consumption	3226.9	5917.3	0.0
Environmental cost (constr.)	249.0	708.1	0.0
Construction cost:	*26131.9 (7%)*	*48118.8 (10%)*	*65745.0 (70%)*
Total:	*418489.4*	*472581.2*	*93480.1*

3.3 Sensitivity analysis using alternative scenarios

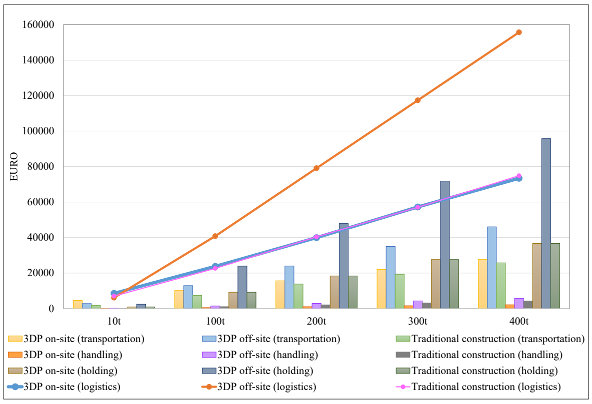

Figure 3. Influence of the variation of raw material quantity on its logistics cost

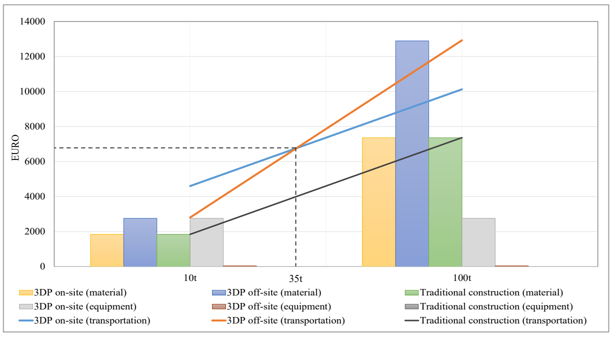

Figure 4. Influence of the variation of raw material quantity on its transportation cost

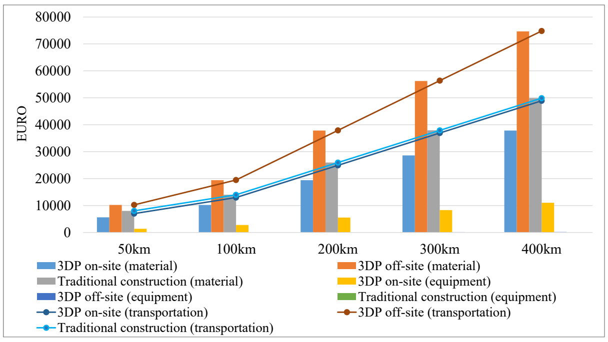

Figure 5. Influence of the distance variation on its transportation cost

The results presented in Table 2 indicate that, apart from the project preparation stage, logistics costs represent the largest proportion of the total cost in 3DP cases. The primary factor influencing logistics costs is the quantity of materials. Therefore, this variable was selected as the independent variable for sensitivity analysis. Recognizing the considerable range of distances between each pair of facilities in the three cases (spanning from 11 to 525km), a decision was made to standardize the distance between each pair of facilities to 100km.This was done to ensure that the calculations are not overly dependent on distance. Figure 3 illustrates the cost elements using clustered columns, while the total logistics costs are represented by lines. In terms of overall logistics cost, off-site 3DP exhibits significantly higher costs compared to the other two cases. It can be observed that the logistics cost for traditional and on-site 3DP is quite similar. Therefore, in this regard, 3DP technology can be considered very comparable despite the need for extensive equipment transportation. Regarding the cost components, transportation and holding costs contribute the most to logistics costs. In real case studies (Table 2), transportation costs tend to dominate due to the large distances between facilities. However, the sensitivity analysis reveals that the holding cost for off-site printed components is quite high. This is associated with the need to hold prefabricated components for 28 days to allow for sufficient strength gain before installation [21]. Implementing effective inventory management practices can help reduce holding costs. Additionally, the use of concrete additives can decrease the time required for strength gain, thus reducing holding costs. The charts indicate an intersection point when considering a small quantity of transported materials, where off-site 3DP demonstrates a more feasible result compared to on-site 3DP, with transportation costs slightly outweighing holding costs.

Therefore, further sensitivity analysis was conducted, focusing solely on transportation costs, including total transportation costs and costs elements associated with material and equipment transportation. Similarly, Figure 4 illustrates the cost elements of material and equipment transportation using clustered columns, while total transportation costs are represented by lines. The intersection between the lines representing on-site and off-site 3DP transportation costs indicates that off-site 3DP techniques can be considered feasible for small object printing, specifically for objects weighing less than 35 tonnes. In general, off-site 3DP becomes more attractive when the cost of delivering printed elements to the construction site is lower than transporting the massive 3D printing equipment along with raw materials.

Another significant factor that impacts transportation costs is the distance traveled. To evaluate the influence of distance variation on the total transportation costs, the distance between any two facilities is designated as the independent variable. Figure 5 presents the results, demonstrating the comparable feasibility of on-site 3DP and traditional construction methods.

4 Conclusions

This study aims to assess the costs associated with

3DP projects compared to traditional construction for low-story buildings. The cost assessment encompasses the project design stage, logistics, construction process with resources used, and waste disposal. Moreover, this model accounts for environmental factors. At the present stage of construction 3DP technology development, the cost of the project preparation stage is 19 times higher than that of traditional construction. However, the construction cost is 2.5 times lower compared to traditional methods. Sensitivity analysis, when compared to comparative analysis (Table 2), provides valuable insights revealing that logistics costs for traditional construction and on-site 3DP are relatively similar. The higher logistics costs of on-site 3DP observed in the comparative analysis can be attributed to the significant distances between suppliers and construction sites. This highlights the need to expand the 3DP materials market to encompass a broader range of traditional construction materials readily available within specific regions. By doing so, transportation costs can be reduced by sourcing materials from local suppliers near the construction site. Furthermore, the sensitivity analysis emphasizes that transportation and holding costs contribute the most to overall logistics costs, highlighting their significance as cost components. The off-site 3DP exhibits higher logistics cost due to holding costs. However, off-site 3DP is more feasible for small-scale projects, such as architecture elements printing, as the cost of delivering printed elements to the construction site is lower compared to transporting the massive 3DP equipment and raw materials. On-site 3D printing can be a competitive alternative to traditional construction methods for individual projects as well as large-scale developments. It is important to note that the model used in this study does not account for breakdowns caused by environmental conditions, equipment failures, or other technical faults.

This study benefits relevant stakeholders in the construction industry, as well as researchers, in the following ways: (1) it provides a comprehensive and structured approach for developing a cost estimation model; (2) the study develops a comprehensive model that plays a pivotal role in evaluating the feasibility of 3DP projects, covering all stages from design to realization; (3) by comparing 3DP scenarios with traditional construction methods, the study highlights the practicality and potential advantages of 3DP projects.

Future advancements in model development can incorporate specific project characteristics, such as geographical location, weather conditions, or remote accessibility, by including surcharge rates tailored to address these factors. To advance the integration of 3DP technology, the subsequent phase involves the technology sustainability assessment and creation of a strategic roadmap. This roadmap will incorporate scientific solutions and serve as a systematic guide, outlining the sequential utilization of the proposed mathematical models to evaluate their cost structure for technology evaluation.

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