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Managing Planning Uncertainty in 3D-Printed Rural Housing Projects Using Monte Carlo Simulation

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Abstract: The use of emerging technologies, such as three-dimensional (3D) printing, in rural housing projects presents an opportunity to transform traditional construction practices, which are often costly, slow and unsustainable. However, the implementation of these technologies faces significant challenges related to uncertainty in planning and execution, particularly because of the lack of historical data and the variability of construction processes. This study evaluates the applicability of Monte Carlo simulation (MCS) as a tool for modelling the duration of a pilot 3D-printed rural housing project, considering both the inherent uncertainty of emerging technologies and the risks associated with external and operational factors. Based on the identification of critical activities and analysis of their probabilistic distributions, the schedule developed using the critical path method (CPM) with a deterministic duration of 56 days has less than 28.7% probability of being met. However, the probability that the actual project duration will not exceed 60 days is estimated at 80%. Additionally, the study identified how fluctuations in activity duration directly affect productivity and increase operational risk, thereby providing valuable insights into improving planning and risk management in similar projects. The results obtained not only help reduce uncertainty in decision-making in similar contexts but also establish a methodological foundation for future research on the effective integration of 3D printing technologies in rural settings. Thus, this study contributes to closing a critical gap in the management of innovative construction projects in regions that face logistical, infrastructural and technological implementation challenges.

Keywords: 3D printing, Monte Carlo simulation, Risk management, Rural housing, Productivity, Planning

INTRODUCTION

The construction industry faces challenges in terms of productivity, despite its fundamental role in the global economy. Progress in the construction sector in the past few decades has remained stagnant, lagging behind that of other key industries. This stagnation is attributed to factors such as resistance to change, low levels of process industrialisation, limited data interoperability and high labour turnover. These issues have resulted in delays, cost overruns and reduced profit margins, affecting both developed and developing economies.

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Additive manufacturing has revolutionised various industries with advantages such as reduced time, lower waste generation, cost savings and mass customisation. In construction, three-dimensional (3D) printing has demonstrated its potential to transform traditional processes through digitalisation and automation. It has emerged as a viable method for increasing productivity and reducing construction costs as it increases resource efficiency while also addressing issues such as the shortage of skilled labour and limitations in building complex shapes without formwork. Moreover, concrete 3D printing (3DCP) has achieved significant progress by enabling rapid and sustainable construction, even under adverse conditions (De Soto et al., 2018; Ayyagari, Chen and De Soto, 2023; Pan et al., 2021; Ahmed, 2023; Waqar, Othman and Pomares, 2023). Nonetheless, the industry is among the least automated and its level of digitalisation is one of the lowest, which hinders the use of advanced technologies (De Soto et al., 2018; Ayyagari, Chen and De Soto, 2023; Khajavi et al., 2021; Pekuss and De Soto, 2020; Zhang et al., 2019; Wu, Wang and Xiangyu, 2016).

In Latin America, traditional construction remains predominant but faces challenges such as high costs, long construction times and significant environmental impacts. Although the region has made progress in the implementation of sustainability measures, these initiatives are still in their early stages and require greater momentum to achieve scalability and transformation within the sector (Inter-American Development Bank, 2024).

3D Construction in Latin America

Digitalisation and the incorporation of innovative technologies, such as industrialised construction and 3D printing, are emerging as key tools for addressing stagnation issues in the construction industry. In particular, 3D printing enables the rapid and efficient production of construction components, reduces material waste and enhances sustainability. However, 3D printing also faces major challenges, including the high cost of machinery, the need for workforce training and the lack of an adequate regulatory framework. Despite these obstacles, 3D printing stands out as an innovative alternative that, although still in the early stages of implementation in Latin America, could transform the sector if it is implemented in a coordinated manner and supported by the public sector (Inter-American Development Bank, 2024).

3D-printed construction projects in Latin America are in the experimental phase, unlike those in regions such as the United States, Europe, and Asia, which are well-established. However, the results achieved in Mexico, Brazil, Chile, Colombia, Guatemala and Peru are promising. For example, in Tabasco, Mexico, 3D printing was used for the construction of resilient housing. The homes built for people living in extreme poverty were designed to withstand natural disasters and adverse climate conditions, highlighting the potential of (Robayo-Salazar et al., 2023). These regional developments in the research and development phase will position 3D printing as an emerging industrial reality in the near future, with a strong focus on sustainability and cost reduction.

A significant example in Colombia was a project underway in the municipality of La Unión, Antioquia, where the first 3D-printed concrete house in South America was built. Led by the municipal government in collaboration with Cementos Argos, the project aimed to transform the housing sector through the use of innovative and sustainable technologies. With the largest 3D printer in the region, houses were built directly onsite, allowing for optimised resource use, cost reduction and accelerated construction times. The walls of the houses were printed within 32 hours, representing a major advancement in sustainable construction in the region (Infobae, 2025). This project addressed the housing deficit in Colombia and demonstrated the potential of 3D printing as an innovative tool in transforming the construction sector, as well as serving as a replicable model for other regions of the country.

One of the most relevant applications of this technology was the construction of housing in remote areas. These areas often face geographic isolation, underdeveloped economies and adverse environmental conditions, which make access to conventional housing solutions unfeasible, difficult and costly (Bazli et al., 2023; Schuldt et al., 2021). 3D printing provides a cost-effective and efficient alternative by reducing the logistics involved in transporting materials and leveraging local resources. Additionally, printers designed to be portable and lightweight facilitate their implementation in these environments, providing an appropriate solution for housing crises in hard-to-reach areas (Schuldt et al., 2021).

Despite its benefits, 3D printing still faces significant challenges. The application of digital manufacturing to large-scale construction is in its early stages and barriers related to the transformation of conventional processes and roles within projects must be addressed. Although there has been a notable increase in 3D printing projects, the applicability and feasibility of this technology have not been evaluated systematically in all contexts. The widespread use of 3D printing is also limited by the lack of clear standards and the need for broader studies to ensure its effective integration into the industry (Ayyagari, Chen and De Soto, 2023; Pan et al., 2021). While significant progress has been made in the study of materials and printing techniques, substantial gaps remain in critical areas, such as the management and planning of projects that incorporate this technology. These aspects are fundamental for the effective and sustained implementation in real-world construction environments.

Managing Uncertainty in 3D Printing Projects

Planning in construction projects constitutes a strategic component essential to ensuring the efficient use of time and resources, as well as proper coordination of activities, risk reduction, and informed decision-making throughout the entire project life cycle. However, common scheduling methods such as the critical path method (CPM) rely on deterministic approaches that assign fixed durations to each activity. This approach does not account for the risks or uncertainties inherent in construction processes, which can result in inaccurate schedules and inefficient resource management, ultimately affecting the ability to meet established deadlines and budgets (Setiawan, Fadjar and Labombang, 2024).

Uncertainty in the actual duration of activities and costs is one of the greatest challenges in project scheduling and execution. This uncertainty is even greater when new technologies are introduced in any industry. In this context, 3D printing presents a new challenge in the management of construction projects. The lack of reliable historical data exacerbates this issue, making it difficult to obtain accurate estimates. This lack of information introduces significant vulnerabilities into project schedules, exposing them to risks of cost overruns and delays (Koulinas et al., 2020; El-Sayegh, Romdhane and Manjikian, 2020). Moreover, estimates based solely on deterministic data do not allow for the development of realistic scenarios, which limits their ability to anticipate and manage risks during both the early and monitoring phases of a project.

In response to these limitations, probabilistic techniques, such as Monte Carlo simulation (MCS), are effective tools for incorporating risk and uncertainty analysis into construction project scheduling. These techniques use probabilistic distributions to model activity duration, providing a more detailed and realistic representation of possible execution scenarios. By considering multiple iterations of potential outcomes, MCS enables better strategic planning and more informed decision-making than traditional methods do (Djohim, Nugroho and Handayani, 2024).

With the introduction of emerging technologies, such as 3D printing, these uncertainties are increased owing to the innovative nature of the process and the limited accumulated experience in its application. In this context, activity scheduling in projects that employ 3D printing presents additional complexities, such as the difficulty of estimating costs and timelines, because available data on this technology is scarce and the planning dynamics differ from those of traditional practices.

The Current Study

Planning procedures that integrate probabilistic techniques to enhance confidence in scheduling and cost estimation for 3D printing projects are necessary. This study focused on the application of MCS as a tool to model the uncertainty associated with the execution times of construction activities in a 3D-printed rural housing project. This tool provides a realistic view of possible project duration scenarios that increase planning capacity. The main objective was to develop a methodological approach based on MCS to estimate the duration of construction activities involved in the 3D printing of walls applied to a pilot case of rural housing. This was to identify critical process variables, model probabilistic behaviour and evaluate the resulting duration scenarios based on the observed variability.

The implementation of this approach aimed to provide a decision-support tool for similar projects, especially during the early stages, when optimising resource allocation and managing risks associated with cost overruns is feasible. This approach would improve project management practices in housing initiatives, particularly in contexts where margins of error must be reduced owing to economic or logistical constraints. In addition, this study can contribute to the growing interest in the use of emerging technologies in construction, which currently lacks a consolidated empirical foundation for adequately managing the uncertainty they generate. The current study focused on the rural regions of southwestern Colombia. In the areas, 3D printing addressed social housing issues, as existing planning approaches perpetuate deterministic frameworks that fail to capture the inherent diversity of construction processes. This disconnection between the applied techniques and the operational conditions of the environment represents a significant source of inefficiency. In addition, this study addressed a gap that has been largely overlooked in the literature, namely, the absence of validated methods for probabilistically estimating execution times in construction processes using 3D printing, particularly in rural contexts. To date, research has primarily focused on urban environments, experimental prototypes or material studies, leaving a gap in terms of tools applicable to operational planning in real-world scenarios. By contributing practical evidence from a pilot case, this study laid the groundwork for new planning approaches adapted to emerging contexts, thereby improving the management of innovative construction technologies.

Nonetheless, this study was limited to the analysis of a small-scale pilot case, which had limitations in terms of generalisability. As a result, the findings of this study only revealed specific conditions that did not necessarily represent the diversity of rural contexts or the variability of 3D printing construction projects. Additionally, the limited availability of historical data on similar regional experiences, particularly in rural settings, made supporting the model parameters with solid empirical evidence difficult.

Therefore, expert judgement was a fundamental methodological resource for estimating durations, defining uncertainty ranges and characterising specific construction processes. Although this approach provided valuable technical insights, it introduced potential biases and subjective elements that must be acknowledged as significant methodological limitations. Nevertheless, the application of this method was appropriate for exploratory research aimed at generating preliminary knowledge and validating approaches before scaling them. Additionally, the study included a general estimate of achievable productivity in the pilot project, calculated based on the results obtained from both deterministic and probabilistic scheduling approaches. This comparison enabled an analysis of how fluctuations in project duration affect the overall performance of the construction process, providing a preliminary measure of productivity that accounts for the uncertainty inherent in the 3D printing context.

LITERATURE REVIEW

Conventional scheduling methods, such as CPM, are based on deterministic approaches that prove to be unreliable and rarely accurate in high-uncertainty contexts. However, uncertainty, especially in the implementation of new technologies, such as 3D printing, can propagate across processes and be intensified owing to the limited availability of historical data or prior references. Therefore, reliable methodologies for both planning and scheduling constitute efficient management of construction projects, particularly those involving advanced technologies, such as 3D printing. The right planning techniques, as well as project management and risk management strategies, allow for greater flexibility and adaptability in the face of uncertain scenarios.

In the literature, various methodologies have been explored to incorporate uncertainty into project planning, including probabilistic scheduling approaches such as the programme evaluation and review technique (PERT) and simulation-based methodologies such as MCS. These methodologies have proven effective in assessing the effects of uncertainty in conventional construction projects. However, their application is particularly relevant in contexts involving new technologies or innovative construction methods such as 3D printing, where the uncertainty associated with durations and risks is significantly greater and complicates planning using deterministic approaches. To illustrate, PERT uses optimistic, most likely, and pessimistic estimates to calculate expected durations and standard deviations analytically, whereas MCS provides a more robust representation of uncertainty through multiple iterations that yield probabilistic results based on predefined distributions for each of the variables involved. Thus, the ability of these tools to model the stochastic behaviour of activities offers a significant advantage for supporting decision-making in highly uncertain environments.

The combined application of the PERT and MCS to generate more realistic construction schedules (Setiawan, Fadjar and Labombang, 2024). This study addressed one of the main limitations of the CPM, which was deterministic because it used a single duration estimate for each activity. The implementation of PERT and MCS allowed for the consideration of variations in duration due to the risks and uncertainties inherent in projects. This approach was particularly useful for identifying the most likely duration ranges and establishing mitigation strategies for potential delays, which was crucial in projects where duration is a key factor for success. Hendradewa (2019) explored the combined application of CPM-PERT and MCS for schedule risk analysis in a residential building project, dividing the analysis into project phases: feasibility study, design and construction. His analysis revealed that although the critical duration estimated using CPM-PERT was 197 days, after running 10,000 MCS iterations, the probability of meeting that duration was only 62.04%. This finding revealed that deterministic methods could significantly underestimate the actual variability and highlights the importance of complementing these approaches with stochastic simulation for more robust planning.

Djohim, Nugroho and Handayani (2024) applied MCS to evaluate the risks associated with 18 activities in a modest housing construction project in Indonesia. In their study, activity durations were obtained through surveys of industry professionals and statistically validated. A total of 2,547 simulation iterations were executed using random combinations of durations according to their probability distributions. This approach allowed for a more reliable estimate of the total project duration and analysed the effects of uncertainties on a project timeline. Additionally, sensitivity and severity analyses identified critical activities, such as wall construction and finishing work, further reinforcing the value of the probabilistic approach in prioritising risk management efforts. To complement this approach, Koulinas et al. (2020) presented a simulation-based expert system for analysing schedule delay risk in construction projects. The system used specific probability distributions for each activity and incorporates project manager preferences obtained through questionnaires. The results showed that this method allowed for a more accurate estimation of the actual project duration by better modelling uncertainty. Additionally, the system was flexible because it could be adjusted for different managerial profiles, ranging from risk-averse to risk-seeking individuals. These contributions emphasised the importance of integrating probabilistic approaches into construction activity planning, particularly in scenarios in which historical data are limited.

By combining CPM with MCS, Mohamed et al. (2020) proposed a simulation-based methodology for risk assessment in wind farm projects. They used a real case study from Ontario, Canada, to give a statistical picture of the project's time and cost. It looked at how this method supported risk-based decision-making in new infrastructure situations. On the other hand, Kurniawan and Mulyono (2024) developed a solution to accelerate delayed construction projects by combining the CPM and PERT, integrating MCS and Primavera software. The case study conducted at PT Freeport Indonesia demonstrates how these methodologies identify critical project activities, assign different time estimates and predict multiple possible outcomes for the accelerated schedule. By applying the "crashing" technique to the schedule, the study reported a probability of 13.9% that the project would be completed in 164 days, increasing the accuracy of the time completion estimates.

Suharni and Lily (2024) addressed the use of the CPM and PERT for project scheduling analysis, with a focus on the fabrication of a pressure vessel for the Bronang Gas Separator project. The study demonstrated how both methods are applied to calculate the total project duration, highlighting the differences between them. CPM proved to be an effective tool for repetitive projects because it relies on single-time estimates, simplifying activity scheduling. However, this approach is less suitable for new projects with high uncertainty, where the activity duration relies on multiple unpredictable factors. In this context, PERT emerged as a more appropriate tool because it accounts for variability in activity durations, allowing for a probabilistic evaluation of project completion. The findings of this study suggested that PERT can optimise scheduling by addressing the inherent uncertainty in complex projects, whereas CPM is more suitable for repetitive projects with more predictable activity durations. Likewise, Deng and Jian (2022) presented a comprehensive approach that combines an improved earned value management (EVM) model with CPM, PERT and MCS. This proposal aimed at mitigating the limitations of the traditional EVM by incorporating uncertainty into the time and cost estimations. Their case study showed that this integration allows for more accurate identification of deviations and prioritisation of critical activities, which is particularly useful in projects involving technological innovation or unconventional construction processes.

Prior literature indicated that scheduling methodologies based on probabilistic analysis and simulation have provided higher levels of confidence than traditional deterministic approaches. The reviewed studies revealed that these methodologies can be applied to all types of construction projects and are particularly suitable for complex or nonconventional projects, where changing conditions, a lack of historical data or the introduction of new technologies result in significantly higher levels of uncertainty. Therefore, projects incorporating innovative techniques, such as 3D printing, can greatly benefit from the use of these tools to enable more robust and realistic planning. Moreover, productivity is recognised as a key indicator in project management because it allows for the evaluation of the feasibility of the proposed schedule. An accurate productivity estimate facilitates efficient resource allocation and the establishment of realistic execution goals. Moreover, its measurement can complement the analyses conducted using probabilistic methods. De Soto et al. (2018) estimated productivity using discrete event simulations with the CYCLONE system, calculating it based on the cost and time per unit installed (e.g., cubic metres of concrete). Their study, which was based on the DFAB HOUSE project, revealed that robotic methods can increase productivity and reduce costs, particularly in the construction of structures with complex geometries. The current study employed a similar approach to evaluate productivity, using the ratio of execution time to installed area. This was based on estimates obtained through both deterministic and probabilistic models, while considering variations in project duration and the inherent uncertainty of the construction process.

The current study employed probabilistic simulations as a method to compare duration outcomes obtained through deterministic scheduling (CPM) and probabilistic scheduling (MCS). Although productivity estimation was not the primary objective of the study, it was included as a complementary analysis to demonstrate how variations in activity duration can affect overall project performance. This approach would reveal the potential effect of implementing probabilistic methodologies in contexts in which technologies such as 3D printing for rural housing introduce new sources of uncertainty to planning. Additionally, the combination of simulation models and probabilistic scheduling enhances confidence in time estimation and facilitates a deeper understanding of the impact of uncertainty on project performance. Thus, the reviewed literature provides a solid methodological foundation for integrating these tools into the planning of construction projects involving emerging technologies.

METHODOLOGY

Objective of the Study

This study aimed to develop a rural housing prototype as part of a pilot 3D-printed construction project by Universidad del Valle in Cali, Colombia (Obando, 2024). Although this study did not address aspects related to the architectural design or structural system of the prototype, general descriptions of its characteristics were included to provide context for the analysis. The focus of this study was limited to the technical analysis of the project from a construction perspective, with an emphasis on the planning and execution of activities involving 3D printing technologies in the construction industry.

This prototype was designed with consideration for the cultural traditions of the Nasa indigenous community who lived in the Cauca Department in the Andean Region of Southwestern Colombia. The Nasa community, also known as the Paéz community, is one of the largest indigenous groups in the country and is characterised by strong social organisation, a deep connection to ancestral territory and a worldview centred on harmony with nature. The design aimed at adapting housing to the needs of the Nasa community by integrating traditional architectural and structural elements with technological innovations that increase the sustainability and resilience of the construction. Figure 1(a) shows the 3D architectural model of the prototype, whereas Figure 1(b) presents the architectural floor plan.

The structural system developed for this house combined the use of posttensioning and sustainable materials, such as *guadua* (*Guadua angustifolia Kunth*), to increase project efficiency. *Guadua* is a giant bamboo species native to Latin America that is widely valued for its mechanical strength, light weight and rapid growth, making it an ideal resource for sustainable construction. The top-tie beam used a system based on PINBOO (an acronym for Pins + Bamboo) technology, which employs *guadua* sheets joined with bolts. The PINBOO system is a construction technique that combines laminated bamboo elements, specifically *guadua*, to allow for efficient, modular and durable joints. This combination of *guadua* and bolts not only creates a lightweight and resource-efficient structure but is also consistent with the sustainability goals of the project by using local materials and traditional construction techniques from the region. The PINBOO beams used as part of the structural system are shown in Figure 1(c).

The structure was based on 3D-printed panels that incorporated posttensioned cables that run vertically through them. These cables were firmly anchored at both the foundation beam and top-tie beam, creating a solid and stable structure. The posttensioning technique, which involved tightening cables after the concrete had cured, optimised the load-bearing capacity of the structure. This was crucial in rural environments, where decreasing long-term maintenance and increasing structural safety are key priorities. This system of printed structural walls is shown in Figure 1(d).

A full *guadua* structure was chosen for the roofing system, taking advantage of its benefits in rural areas of Colombia. *Guadua* provides good thermal comfort and easy assembly. For roof coverings, the use of unplasticized polyvinyl chloride (uPVC) tiles was proposed because of their light weight, durability and corrosion resistance, complementing the roofing solution in terms of both efficiency and sustainability. The bamboo roof structure is illustrated in Figure 1(E). This hybrid structural system, which integrates post-tensioned cables, *guadua* and innovative technological solutions, represents a pioneering approach to rural construction in Colombia. This prototype aimed to improve the quality of life in the rural areas of Cauca, while respecting and reinforcing the cultural traditions of the Nasa community by offering a robust, ecological and locally adapted alternative.

The diagrams and schematics related to the object of study, which show the design and integration of the structural and technological components, were gathered through a review of documents and interviews with participants in the 3D printing pilot project at the Universidad del Valle. These diagrams are shown in Figure 1 to present details of the proposed modular system for rural housing.

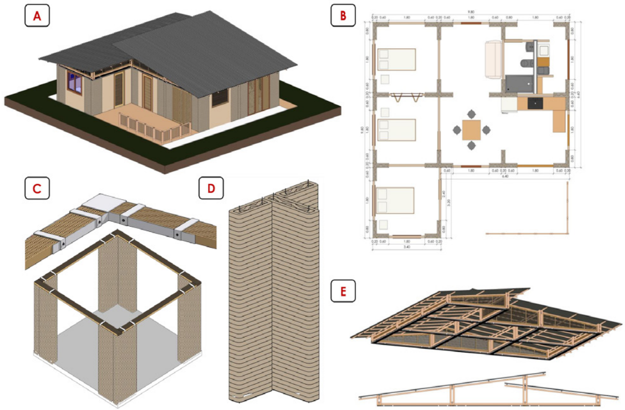

Figure 1. Adaptable modular structural system with 3D printing for rural housing in the Department of Cauca, Colombia: (a) 3D architectural model of the housing prototype, (b) architectural floor plan, (c) PINBOO beams, (d) printed structural walls and (e) bamboo roof structure

Source: Obando (2024)

The configuration and operating environment of the commercial gantry-type 3D printer utilised in this study are shown in Figure 2. The printer was selected owing to its advanced technical features that met the specific requirements of the case study. Its modular structure allowed it to adapt to the particular dimensions and shapes of each project, making it a flexible and highly adaptable tool for on-site construction. In addition, its ability to print at high speed and precision makes it an ideal option for optimising the efficiency of the construction process, and it was considered one of the fastest printers on the market. In addition, the modular printer system allowed for size adjustment according to the needs of projects of different scales. In this case, the area of the prototype to be printed was 96.04 m^2, so the printer was configured with five modules along the X and Y axes and two modules along the Z axis. These modules referred to structural segments that comprised the rails and vertical columns of the printer, which could be assembled or dismantled to adjust its spatial reach in each direction. This configuration resulted in a printable volume of 12.10 m × 11.53 m × 3.49 m along the X, Y and Z axes, respectively. With this setup, a total print area of 139 m^2 was ensured, guaranteeing that the printer can meet the specific requirements of the project. This 3D space corresponded to the operational volume within which the physical printing of the building components occurred (as shown in Figure 2[a]). Meanwhile, Figure 2(b) shows the required installation volume. The volume referred to the physical space necessary for assembling, operating and manoeuvring the printer and its auxiliary components. This included safety margins, access areas, circulation paths and space for positioning additional equipment, all of which are essential for adequately planning the site conditions.

Figure 2 was generated using a web tool provided by the manufacturer and shows both the modular configuration of the printer and a representation of the surrounding area and complementary system elements. The primary objective of this figure was to show the potential equipment that would be used during project execution. Therefore, the figure was informative and details the possible technical requirements in terms of the equipment necessary to carry out the 3D printing process and increase its effectiveness.

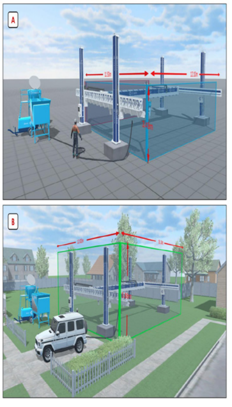

Figure 2. Configuration of the modular gantry 3D printer selected for the rural housing project: (a) Configured printable volume, representing the spatial range within which the components are physically printed and (b) Required installation space, indicating the total physical area necessary for the setup, safe operation and auxiliary systems around the printer

Source: Retrieved from https://cobod.com/configurator/ on 26th November 2024

RESEARCH METHODS

The methodology combined MCS and CPM to identify project risk-simulation effects and generate a probabilistic estimate of execution time. This methodology involved several key stages: (1) definition of construction processes, (2) estimation of activity durations, (3) project activity scheduling, (4) MCS and (5) productivity estimation. The flow is displayed in Figure 3.

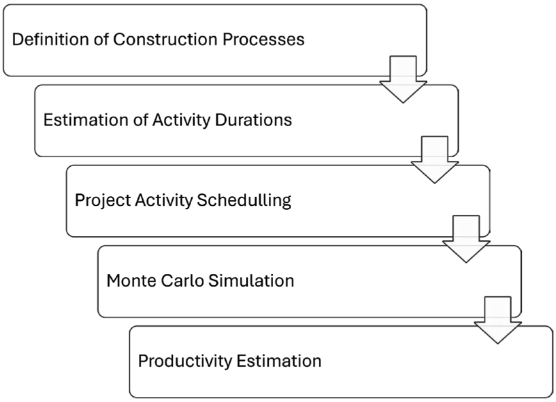

Figure 3. Methods

Definition of Construction Processes

The construction process was defined through the development of a work breakdown structure (WBS). WBS provided a clear and detailed view of the project scope. It organised the activities required for the construction of the prototype into five main categories: (1) site preparation, (2) foundation construction, (3) main structure construction, (4) MEP installations (mechanical, electrical and plumbing) and (5) architectural finishes. A total of 20 key activities were defined, including tasks such as site preparation, construction of foundation beams, 3D printing of walls, installation of plumbing, sanitary and electrical systems and the application of final finishes.

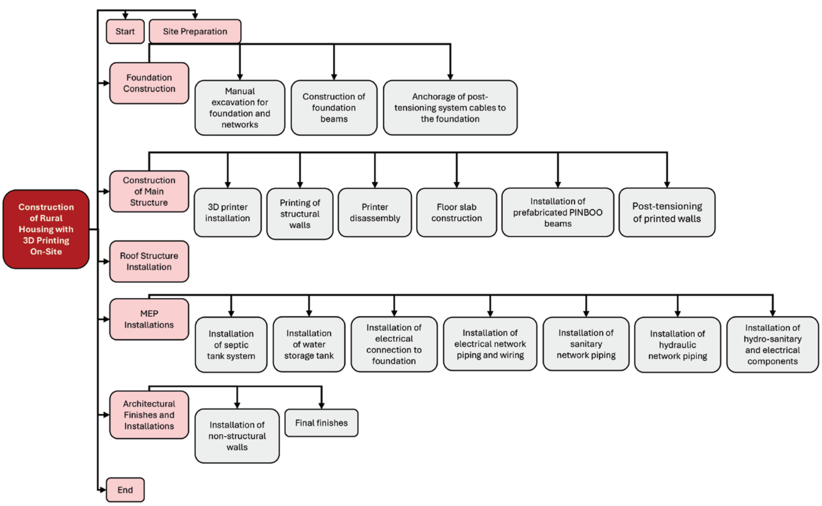

Figure 4. Work breakdown structure

Estimation of Activity Durations

The estimation of activity duration was calculated through a qualitative analysis of expert judgement (as shown in Table 1). The three-point estimation technique described in the *PMBOK® Guide* (Project Management Institute, 2021) was used to estimate the duration of the activities based on the individuals involved in project planning. This approach incorporated uncertainty and variability into the execution times, providing a comprehensive view of the range of possible durations. This method considers three key values: (1) the most likely duration, which represented the estimated time under normal execution conditions, considering average factors such as resource availability, typical weather conditions and standard productivity, (2) the optimistic duration, which represented the minimum possible time under ideal conditions, no interruptions and full resource availability and (3) the pessimistic duration, which corresponded to the maximum time required under adverse conditions, including interruptions, logistical issues and low productivity. This detailed analysis enabled the accurate capture of potential variations in activity duration, supporting more realistic and reliable planning.

Table 1. Time data under uncertainty

ID	Task	Duration (Days)		
		Optimistic	**Most Likely**	**Pessimistic**
A	Site preparation	2.0	3.0	5.0
B	Manual excavation for foundation and networks	2.0	3.0	5.0
C	Construction of foundation beams	5.0	7.0	10.0
D	Anchorage of posttensioning system cables to the foundation	1.5	2.0	4.0
E	3D printer installation	4.0	6.0	9.0
F	Printing of structural walls	3.0	4.0	6.0
G	Printer disassembly	3.0	4.0	6.0
H	Floor slab construction	1.5	2.0	3.5
I	Installation of prefabricated PINBOO beams	3.0	4.0	6.0
J	Posttensioning of printed walls	2.5	3.0	5.0
K	Roof structure installation	5.0	7.0	10.0
L	Installation of septic tank system	2.0	3.0	5.0
M	Installation of water storage tank	1.5	2.0	3.5

(*Continued on next page*)

Table 1 *Continued*

ID	Task	Duration (Days)		
		Optimistic	Most Likely	Pessimistic
N	Installation of electrical connection to foundation	1.5	2.0	3.5
O	Installation of electrical network piping and wiring	1.5	2.0	3.5
P	Installation of sanitary network piping	0.8	1.0	2.0
Q	Installation of hydraulic network piping	0.8	1.0	2.0
R	Installation of hydro-sanitary and electrical components	2.0	3.0	5.0
S	Installation of non-structural walls	4.0	6.0	8.0
T	Final finishes	5.0	7.0	10.0

Project Activity Scheduling

Project activities were scheduled using CPM. The most likely activity durations were previously determined based on data collection served as the basis for developing a schedule with deterministic durations. Table 2 outlines the activity schedule, including detailed durations, sequence, and precedence relationships. Based on this information, an activity network diagram was created. Figure 5 illustrates the diagram that allowed for the identification of critical paths, which were highlighted in red boxes and the calculation of the total time required to construct the rural housing prototype. The network showed the logical sequence of the activities and their interdependencies. According to the analysis, the estimated time to complete the construction of the prototype was 56 days.

Table 2. Deterministic project schedule

ID	Task Name	Duration (Days)	Start	Finish	Predecessors
1	Construction of rural housing with 3D printing on-site	56	1st January 2025	19th March 2025	
2	Start	–	1st January 2025	1st January 2025	
3	Site preparation (A)	3	1st January 2025	3rd January 2025	2
4	Foundation construction	8	14th January 2025	23th January 2025	
5	Manual excavation for foundation and networks (B)	3	14th January 2025	16th January 2025	9
6	Construction of foundation beams (C)	7	15th January 2025	23th January 2025	5SS+1d
7	Anchorage of posttensioning system cables to the foundation (D)	2	17th January 2025	20th January 2025	6SS+2d
8	Construction of main structure	33	6th January 2025	19th February 2025	
9	3D printer installation (E)	6	6th January 2025	13th January 2025	3
10	Printing of structural walls (F)	4	29th January 2025	3rd February 2025	6FS+3d;7
11	Printer disassembly (G)	4	4th February 2025	7th February 2025	10
12	Floor slab construction (H)	2	10th February 2025	11th February 2025	11;21;18
13	Installation of prefabricated PINBOO beams (I)	4	13th February 2025	18th February 2025	10FS+7d;12
14	Post tensioning of printed walls (J)	3	17th February 2025	19th February 2025	13SS+2d
15	Roof structure installation (K)	7	20th February 2025	28th February 2025	14;13

(*Continued on next page*)

Table 2 *Continued*

ID	Task Name	Duration (Days)	Start	Finish	Predecessors
16	MEP installations	45	14th January 2025	17th March 2025	
17	Installation of septic tank system (L)	3	14th January 2025	16th January 2025	5SS
18	Installation of water storage tank (M)	2	17th January 2025	20th January 2025	17
19	Installation of electrical connection to foundation (N)	2	15th January 2025	16th January 2025	5SS+1d
20	Installation of electrical network piping and wiring (O)	2	3rd March 2025	4th March 2025	15;19
21	Installation of sanitary network piping (P)	1	17th January 2025	17th January 2025	17
22	Installation of hydraulic network piping (Q)	1	21st January 2025	21st January 2025	18
23	Installation of hydro-sanitary and electrical components (R)	3	13th March 2025	17th March 2025	20;21;22;26SS+2d
24	Architectural finishes and installations	13	3rd March 2025	19th March 2025	
25	Installation of nonstructural walls (S)	6	3rd March 2025	10th March 2025	15
26	Final finishes (T)	7	11th March 2025	19th March 2025	15;25
27	End	–	19th March 2025	19th March 2025	23;26

Note: SS and FS indicate start-to-start and finish-to-start sequence relationships, respectively.

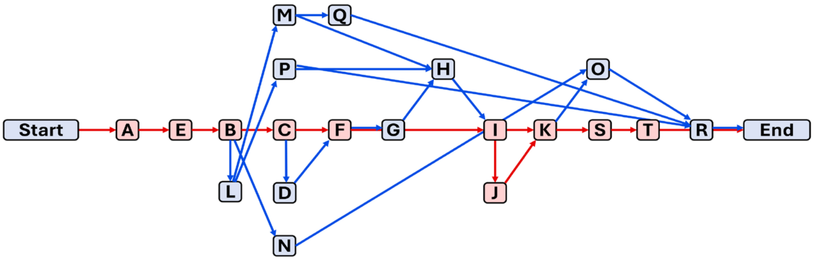

Figure 5. Project network diagram

Monte Carlo Simulation

MCS was applied using @Risk software, an add-in for Microsoft Excel, to evaluate the total time and cost of constructing the prototype while accounting for the variability observed in the collected data. The activity network scheduled using CPM was transferred from Project to Excel, integrating the estimated durations and their logical relationships. For each activity, the minimum, maximum and most likely duration ranges were defined using PERT-type probability distributions, which assigned a higher probability to values near the most likely estimate and lower probabilities to the extremes.

Using @Risk, 1,000 iterations were performed. This aimed to generate probabilistic distributions of time and cost, allowing for more reliable scenario assessments. Then, the analysis was taken in three main steps: first, replacing the fixed duration and cost values with probability distributions; second, selecting key outputs, such as total project duration and total labour cost; and third, executing the simulations. In each iteration, @Risk was sampled randomly from the defined distributions, the values were applied to the model and the results were recorded. This process provided a comprehensive view of the potential scenarios and improved the decision-making foundation.

Productivity Estimation

The goal of this phase was to estimate productivity both deterministically and based on the simulation results, allowing for a comparison between the two estimates. This approach provided a more comprehensive view of process productivity in terms of time by considering the variability of the estimates and the uncertainty inherent in the project. Thus, in the productivity estimation stage, the productivity indices of the construction process were calculated on the basis of the results obtained from MCS. Productivity (P) was estimated using the following equation (De Soto et al., 2018):

$$P = Q/I \quad \text{Eq. 1}$$

where Q represented the quantity installed (square metres of the constructed area) and *I* represented the total input in terms of time. The outcome suggested that a reduction in time per installed unit represented the process's efficiency.

RESULTS AND DISCUSSION

The results obtained from MCS presented two key findings. First, the cumulative density curve, estimated by the deterministic CPM, revealed that the probability of a project being completed within 56 days was less than 28.7% (as shown in Figure 6). This result indicated that the projected duration had a considerable level of uncertainty, with in most simulated scenarios, the completion time would exceed 56 days. Second, the probability density distribution chart (as shown in Figure 7) illustrates how probabilities were distributed across different estimated durations, allowing for a visual understanding of the likelihood of project completion within a given timeframe. According to the figure, the probability of a project duration falling between 54 and 60 days was 80%. Additionally, the probability that the project will be completed in less than 54 days was 10% and more than 60 days was 10%. The findings indicated the time ranges within which a project is likely to be completed. These results highlighted the importance of considering probabilistic ranges for planning rather than relying solely on the point estimate provided by the CPM, which may not adequately reflect project uncertainties.

These findings align with those of Hendradewa (2019), who applied a combined CPM-PERT methodology with MCS to estimate the duration of a residential building project. The study concluded that deterministic estimates tend to underestimate the actual variability. This finding was confirmed by the notion that the critical duration estimated by CPM-PERT (197 days) had only a 62.04% probability of being met according to the simulation results. Similarly, Mohamed et al. (2020) reported that techniques such as PERT and MCS are effective tools for providing more accurate estimates in construction projects characterised by high uncertainty, particularly for nonstandardised or underexplored construction processes, such as onshore wind farms or, in this study, 3D printing.

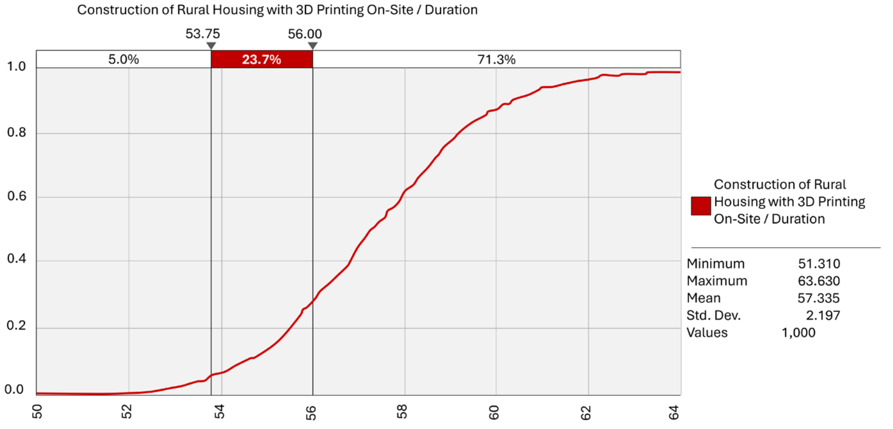

Figure 6. Cumulative density curve of total project duration based on MCS

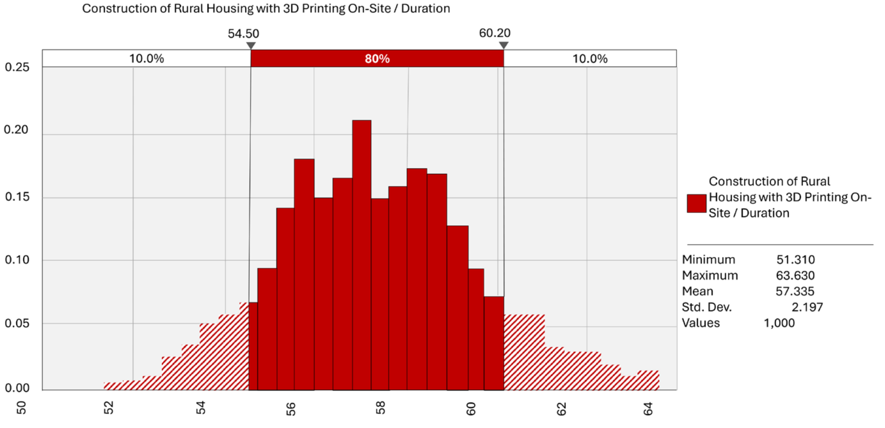

Figure 7. Probability density function of project duration according to MCS

Figures 8 and 9 present the results of the sensitivity analysis via tornado diagrams. The charts highlight the effect of each activity on the overall project duration. Figure 8 shows the contribution of each activity to the project duration variance. This chart highlights the activities with the greatest effect on the time-related uncertainty of the project. The activities such as the construction of foundation beams, roof assembly, printer installation and final finishes had the most significant effect on the variability of the project duration, contributing approximately 17% to 19% of the total deviation in execution times. In short, Figure 8 shows the critical elements that must be managed to reduce the risk of project delays.

Moreover, Figure 9 classifies activities on the basis of their maximum and minimum values, showing how random parameters can affect the duration in comparison with the baseline, defined by the mean duration. This analysis revealed the potential range of variation that each activity might integrate into the total project duration. Figure 9 also ranks the inputs according to their direct effect on the project duration. The activities represented in this chart could either increase or decrease the total project duration within an estimated range between 56 and 59 days, depending on the performance during execution. The findings highlighted the potential effect of parameter variations on the overall schedule.

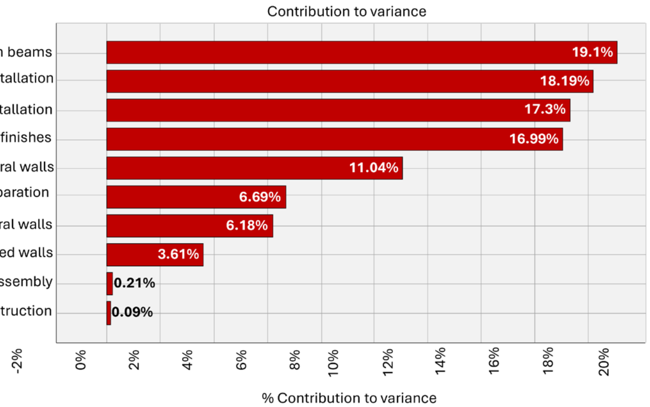

Figure 8. Tornado diagram of the contribution to project duration variance

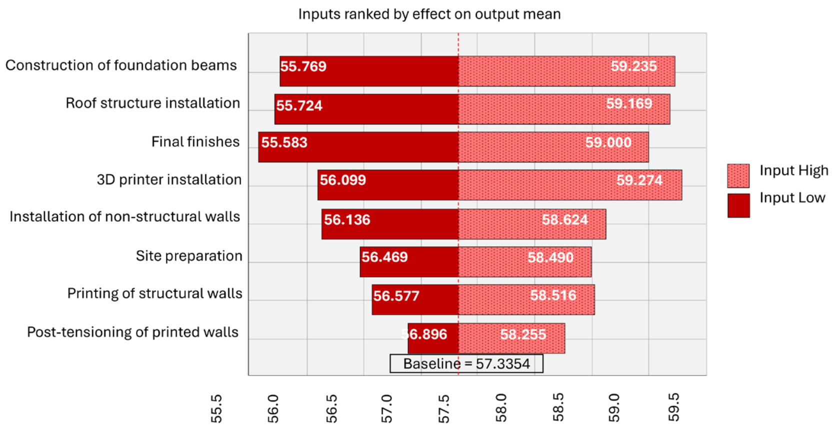

Figure 9. Tornado diagram ranking activities by maximum and minimum project duration values

Other studies have used sensitivity analysis to prioritise critical activities in the context of uncertainty. For example, Deng and Jian (2022) integrated MCS with enhanced EVM metrics, CPM and PERT to estimate the possible completion range of a project, identifying activities with the greatest effect on time and cost deviations. Their approach highlighted certain activities because of their significant contribution to the overall project uncertainty. Although the case study and activities considered differ from those addressed in the current study, both studies focused on the application of probabilistic approaches to identify the sources of uncertainty that highly affect total project duration.

Additionally, Suharni and Lily (2024) emphasised that CPM is suitable for repetitive projects, where activities rely on single-time estimates. However, applying this approach to new projects, where the duration depends on multiple uncertain factors, was difficult. In these cases, the uncertainty about activity completion generated variability in completion times. Because this variability could not be accurately predicted, the use of PERT was essential because it enabled better management of uncertainty in projects where time estimates were less predictable, unlike CPM, which was more effective in projects with more consistent activity durations. This approach was consistent with the issues addressed in this study because construction via 3D printing departed from the context of conventional construction, for which more stable and easily transferable information existed.

In the final stage of the study, the productivity of the construction process was estimated in terms of time, with the installed quantity of 96.04m^2 as a reference. Calculations were performed for three scenarios: the deterministic schedule of 56 days according to the CPM and confidence interval limits of 80% (54 and 60 days), which were obtained from the probability density function generated by the MCS. Productivity, expressed in square metres per day (m^2/day), was calculated using Equation 1. The results are summarised in the following Table 3.

Table 3. Productivity based on the time per unit installed

Scenario	Duration (Days)	Productivity (m^2/day)
Deterministic (CPM)	56	1.715
Lower limit (80%)	54	1.779
Upper limit (80%)	60	1.601

Table 3 reveals that in the deterministic scenario, the estimated productivity was 1.715m^2/day, with productivity varying between 1.779m^2/day (lower limit) and 1.601 m^2/day (upper limit) within the 80% confidence range. This variability indicated the effect of fluctuations in project duration on the efficiency of the construction process. A shorter execution time results from higher productivity, whereas longer durations indicate lower productivity. However, the observed variation in productivity was 10.9%, which was relatively small. This finding suggested that the proposed construction process was efficient and consistent even under fluctuations within the 80% confidence range. In the specific case of the small-scale project under study, variation had a limited effect because the accumulated time differences were not significant. Nevertheless, in larger-scale projects, variations could become more relevant because small improvements in daily productivity could translate into significant reductions in construction time and total costs. These results highlight the importance of considering probabilistic ranges when the goal is to obtain more robust and realistic estimates. Recent studies, such as that of De Soto et al. (2018), have shown similar patterns in 3D construction systems, where productivity is sensitive to duration but remains relatively stable under controlled conditions. These findings confirmed the feasibility of 3D printing for small-scale housing projects.

CONCLUSION

This research demonstrated the usefulness of MCS as a tool for evaluating the duration of construction projects under uncertain conditions associated with new 3D printing technologies, which lacked historical data for construction planning. The simulation determined that a projected duration, according to the deterministic CPM, did not adequately capture the potential variabilities inherent in the construction process. The study findings indicated that the probability of meeting the initially estimated 56 days was less than 28.7%, whereas with an 80% confidence level, the likely duration could reach up to 60 days. This probabilistic approach highlights the need to complement traditional methodologies with more robust analyses that consider planning uncertainty. From a theoretical perspective, this study provides empirical evidence of the limitations of conventional planning approaches in non-standardised processes and supports the use of stochastic models to represent operational uncertainty better. Practically, the methodology allows for the prioritisation of critical activities, such as foundation construction, roof assembly and printer installation, through sensitivity analysis, which eventually facilitates more efficient resource allocation and proactive risk management.

The productivity of the system showed moderate variability (10.9%) within the range of 1.601 m^2/day to 1.779 m^2/day at an 80% confidence level, suggesting a relatively stable construction process, although with important implications for larger-scale projects. Applying this model to technologies such as 3D printing enables the generation of more realistic estimates and supports informed decision-making in the planning of rural housing, as the lack of data is a recurring challenge. In addition, probabilistic simulation represents a methodological advancement that increases the confidence of time estimates and improves the identification of risks, adding value to both the theoretical body of project planning and its practical application. Future research may extend this approach to larger-scale projects and incorporate variables such as cost and resource availability for comprehensive risk management in construction with disruptive technologies.

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