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Application of Utility Function for Optimization and Ranking of Concrete Mix Designs

Alireza Rasekhi Sahneh; Abuzar Masoumi

DOI:

Faculty member, Civil Engineering Department, Qeshm Branch, Islamic Azad University, Qeshm, Iran.

*** Corresponding author:** Alireza.rasekhi@iau.ac.ir

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ABSTRACT

Calcium aluminate cement is considered a special cement due to its unique structure and the presence of at least 40% aluminum oxide. It is highly durable under severe environmental conditions. However, challenges such as high cost and more importantly, sudden reduction in strength have limited its use as a standalone cement without structural modifications through alternative materials. The wide variety of these materials and their diverse effects on the various properties of this cement increase the number of variables, often causing confusion among engineers when selecting materials in different proportions. In this study, 20 mix designs were prepared with replacement percentages of 40%, 25%, 15%, 5%, and 60% of alternative materials including zeolite, slag, pumice, and limestone powder, and compared with a control mix. Subsequently, using the utility function, a concept from mathematics, the mixes were ranked from technical and economic perspectives.

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Introduction

Concrete containing calcium aluminate cement has been used in civil engineering projects for over 100 years. This cement initially gained attention due to its high early strength in the construction of weapon storage facilities during World War I in France [1]. Today, it has various applications, including as a heat-resistant material in refractory industries [2-4] and as a material resistant to acidic and corrosive environments such as industrial floors and sewage pipes [5-6]. Another important advantage of this cement is its ability to gain rapid strength even at low temperatures (around zero degrees Celsius), which is why calcium aluminate cement is recognized in North America as a fast-setting repair material [7-8]. Despite its strengths, the widespread use of this cement is limited for two main reasons: its cost, which is about ten times higher than Portland cement, and a sudden reduction in strength over time.

A solution proposed by previous researchers to address these two weaknesses is the use of cement replacement materials [9]. In this study, as described below, 21 mix designs were prepared, various tests were conducted on them, and the cost of each mix design was calculated based on current market prices in Iran.

2. Materials and Methods:

Calcium aluminate cement is highly capable of durability under severe environmental conditions. However, as mentioned earlier, issues such as the high cost of the product and more importantly, the sudden reduction in strength, have limited the use of this cement alone without certain modifications in its structure by using replacement materials. One of the most important concerns in the production of any product or material today is cost reduction during the manufacturing process. However, ignoring technical parameters and focusing solely on cost reduction cannot lead to the production of a suitable and widely used product. Therefore, first and foremost, any product must be technically acceptable, which is a higher priority, and then cost considerations should be addressed.

The wide variety of materials and their diverse effects on various properties of this cement increase the number of variables and sometimes cause confusion among engineers when selecting materials at different proportions. In this study, after preparing 20 mix designs with replacement percentages of 40%, 25%, 15%, 5%, and 60% of alternative materials including zeolite, slag, pumice, and limestone powder, these were compared with a control sample. Then, using the utility function, the mixes were ranked from technical and economic perspectives. In this research, the code for each mix design indicates the type of material used and the replacement percentage of cement. For example, the code **C** refers to the control sample (without replacement materials), **Z25** indicates a mix with 25% zeolite replacement, **P** stands for pumice, and **L** and **S** represent limestone powder and slag, respectively. In this study, mechanical properties, durability, and construction cost are the dependent variables which change according to various independent factors. Therefore, considering the number of dependent variables (more than one), to find the optimal mix design or to rank all mixes, it is necessary to use a multivariate optimization method called the utility function. One of the efficient and suitable methods in this regard is the method proposed by Smith [10].

$$\mathrm{d_j} = \left[\frac{\mathrm{Y_j} - \min f_\mathrm{j}}{\max f_j - \min f_j}\right]^{t_j} \tag{1}$$

(2)

$$d_j = \left[\frac{\max f_j - Y_j}{\max f_j - \min f_j}\right]^{t_j}$$

(3)

$$D = (d_1 \times d_2 \times d_3 \times \ldots \times d_m)^{\frac{1}{m}}$$

In the above equations, djd_jdj represents the utility function value, YjY_jYj is the response, maxfj\max f_jmaxfj is the maximum response value for the jthj^{th}jth criterion, minfj\min f_jminfj is the minimum response value for the jthj^{th}jth criterion, tjt_jtj is the weighting parameter for the jthj^{th}jth criterion, DDD is the objective function, and mmm is the number of criteria.

The utility function for criteria such as compressive strength, flexural strength, modulus of elasticity, and electrical resistance, where a higher value is desirable, was obtained using Equation (1). For criteria such as chloride ion migration coefficient, volume of permeable pores, and cost, where a lower value is preferred, the utility function was calculated using Equation (2). Then, the overall utility function DDD as the objective function was calculated according to Equation (3). The utility function value ranges between 0 and 1, where 1 represents the highest desirability and 0 indicates the lowest or no desirability. The weighting parameter tjt_jtj reflects the relative importance of each criterion compared to others.

In this study, both technical and economic criteria were considered. Based on interviews and surveys with 10 experts active in the concrete field, the weighting parameter for economic criteria was assigned a coefficient of 1, and for technical criteria—due to their connection with safety and structural stability—a coefficient of 2 was assigned. Therefore, tjt_jtj was set to 2 for technical criteria and 1 for economic criteria.

3. Research Findings and Data Analysis

3-1 Technical Evaluation

To produce durable and satisfactory concrete, the selection and application of mixes should be based on combined mechanical properties and durability. In this study, for technical evaluation, three mechanical properties—compressive strength, flexural strength, and modulus of elasticity—and three durability components—accelerated chloride ion migration, volume of permeable voids, and electrical resistance—were all measured at 90 days.

Tables (1) to (6) show the calculated utility coefficients for the six mentioned criteria, each individually based on Equations (1) or (2). Table (7) presents the technical utility coefficient for the mix designs considering all six mechanical and durability factors simultaneously, calculated using Equation (3). Finally, Table (8) ranks the mix designs from 1 to 21.

The results of Table (1) indicate that approximately all mixes containing pumice, zeolite, and slag exhibited better compressive strength performance compared to the control sample. The best mix designs in this regard were, in order: S40, Z40, Z25, and P40. The weakest mixes were L40 and L60. Another noteworthy point is that mixes with 60% replacement (except L60) performed similarly or even better than the control mix. A similar trend is observed for flexural strength and modulus of elasticity, as shown in Tables (2) and (3).

From a durability perspective (results in Tables 4 to 6), the impact of replacement materials was more pronounced than on mechanical properties, as the obtained utility coefficients were closer to 1 or showed significant differences compared to the control sample's utility coefficients. Another important point is the utility coefficient of the control sample for mechanical and durability properties. This coefficient was slightly below average for mechanical properties but was very low for durability, indicating low desirability of the durability component and highlighting the need for special attention to durability issues in this type of cement. The results show that, in terms of durability, the best mix designs are Z40, Z25, P40, and S40.

Table (1): Utility Coefficient of Compressive Strength for Mix Designs (MPa)

Compressive Strength Utility	Maximum Compressive Strength	Minimum Compressive Strength	Compressive Strength	Sample
0.45	46.5	5.5	24.10	C
0.64			31.90	Z5
0.70			34.30	Z15
0.90			42.50	Z25
0.98			45.80	Z40
0.60			30.20	Z60
0.49			25.70	S5
0.64			31.90	S15
0.72			35.00	S25
1.00			46.50	S40
0.40			22.10	S60
0.62			30.90	P5
0.63			31.20	P15
0.71			34.50	P25
0.73			35.30	P40
0.56			28.60	P60
0.34			19.5	L5
0.31			18.4	L15
0.48			25.3	L25
0.15			11.7	L40
0.01			5.5	L60

Table (2): Utility Coefficient of Flexural Strength of Mix Designs (MPa)

Flexural Strength Utility Coefficient	MinimumFlexural Strength	MinimumFlexural Strength	Flexural Strength	Sample
0.40	2.9	0.75	1.60	C
0.72			2.30	Z5
0.77			2.40	Z15
0.86			2.60	Z25
1.00			2.90	Z40
0.40			1.60	Z60
0.58			2.00	S5
0.63			2.10	S15
0.67			2.20	S25
0.86			2.60	S40
0.49			1.80	S60
0.63			2.10	P5
0.72			2.30	P15
0.77			2.40	P25
0.95			2.80	P40
0.40			1.60	P60
0.35			1.50	L5
0.21			1.20	L15
0.07			0.90	L25
0.02			0.80	L40
0.01			0.75	L60

Table (3): Utility Coefficient of Elastic Modulus of Mix Designs (MPa)

Elastic Modulus Utility Coefficient	Maximum Elastic Modulus	Minimum Elastic Modulus	Elastic Modulus	Sample Code
0.41	47	8.1	24.00	C
0.72			36.0	Z5
0.74			37.0	Z15
0.85			41.0	Z25
1.00			47.0	Z40
0.47			26.3	Z60
0.89			42.9	S5
0.82			40.1	S15
0.70			35.4	S25
0.90			43.3	S40
0.50			27.4	S60
0.51			28.0	P5
0.61			32	P15
0.72			36	P25
0.90			43	P40
0.46			26	P60
0.36			22.1	L5
0.27			18.6	L15
0.19			15.4	L25
0.11			12.3	L40
0.01			8.1	L60

Table (4): Utility Coefficient of Accelerated Chloride Ion Migration of Mix Designs ($\times 10^{-12}$ m²/s)

Utility Coefficient of Accelerated Chloride Ion Migration	Minimum Migration Coefficient	Maximum Migration Coefficient	Migration Coefficient	Sample Code
0.53	0.9	12	6.10	C
0.71			4.1	Z5
0.73			3.9	Z15
0.85			2.6	Z25
1.00			0.9	Z40
0.97			1.2	Z60
0.69			4.3	S5
0.80			3.1	S15
0.92			1.8	S25
0.96			1.3	S40
0.58			5.6	S60
0.64			4.9	P5
0.67			4.61	P15
0.68			4.43	P25
0.96			1.32	P40
0.88			2.24	P60
0.51			6.3	L5
0.43			7.2	L15
0.47			6.8	L25
0.45			7.0	L40
0.01			12.0	L60

Table (5): Utility Coefficient of Electrical Resistivity of Mix Designs (kΩ·cm)

Electrical Resistivity Utility Coefficient	Maximum Electrical Resistivity	Minimum Electrical Resistivity	Electrical Resistivity	Sample Code
0.02	167.2	18.4	21.30	C
0.12			36.6	Z5
0.36			72.6	Z15
0.62			110.3	Z25
1.00			167.2	Z40
0.34			68.3	Z60
0.09			32.0	S5
0.01			18.4	S15
0.07			28.9	S25
0.44			84.0	S40
0.22			50.9	S60
0.02			22.1	P5
0.05			25.6	P15
0.44			83.2	P25
0.59			106.3	P40
0.42			81.3	P60
0.00			18.5	L5
0.03			23.1	L15
0.03			23.6	L25
0.01			20.1	L40
0.01			19.5	L60

Table (6): Utility Coefficient of Accessible Pore Volume in Mix Design

Permeable Pores Utility Coefficient	Minimum Volume of Permeable Pores (%)	Maximum Volume of Permeable Pores (%)	Volume of Permeable Pores (%)	Sample Code
0.01	6.90	10.5	10.50	C
0.61			8.30	Z5
0.89			7.30	Z15
0.94			7.10	Z25
1.00			6.90	Z40
0.81			7.60	Z60
0.56			8.50	S5
0.86			7.40	S15
0.89			7.30	S25
0.94			7.10	S40
0.75			7.80	S60
0.50			8.70	P5
0.75			7.80	P15
0.81			7.60	P25
0.89			7.30	P40
0.72			7.90	P60
0.67			8.1	L5
0.61			8.3	L15
0.36			9.2	L25
0.17			9.9	L40
0.33			9.3	L60

Table (7): Technical Utility Coefficient of the Mix Design

Void Volume Utility Coefficient	Chloride Ion Penetration Utility Coefficient	Chloride Ion Penetration Utility Coefficient	Electrical Resistance Utility Coefficient	Elastic Modulus Utility Coefficient	Flexural Strength Utility Coefficient	Compressive Strength Utility Coefficient	Sample Code
0.02	0.01	0.53	0.02	0.41	0.4	0.45	C
0.26	0.61	0.71	0.12	0.72	0.72	0.64	Z5
0.45	0.89	0.73	0.36	0.74	0.77	0.7	Z15
0.69	0.94	0.85	0.62	0.85	0.86	0.9	Z25
0.98	1	1	1	1	1	0.98	Z40
0.31	0.81	0.97	0.34	0.47	0.4	0.6	Z60
0.2	0.56	0.69	0.09	0.89	0.58	0.49	S5
0.13	0.86	0.8	0.01	0.82	0.63	0.64	S15
0.27	0.89	0.92	0.07	0.7	0.67	0.72	S25
0.67	0.94	0.96	0.44	0.9	0.86	1	S40
0.21	0.75	0.58	0.22	0.5	0.49	0.4	S60
0.11	0.5	0.64	0.02	0.51	0.63	0.62	P5
0.19	0.75	0.67	0.05	0.61	0.72	0.63	P15
0.46	0.81	0.68	0.44	0.72	0.77	0.71	P25
0.67	0.89	0.96	0.59	0.9	0.95	0.73	P40
0.27	0.72	0.88	0.42	0.46	0.4	0.56	P60
0.05	0.67	0.51	0.01	0.36	0.35	0.34	L5
0.05	0.61	0.43	0.03	0.27	0.21	0.31	L15
0.03	0.36	0.47	0.03	0.19	0.07	0.48	L25
0.006	0.17	0.45	0.01	0.11	0.02	0.15	L40
0.004	0.33	0.01	0.01	0.01	0.01	0.01	L60

Table (8): Ranking of Mixture Designs Based on Technical Desirability

Sample Rank	Technical Utility Coefficient (Mechanical Properties and Durability)	Sample Code
1	0.98	Z40
2	0.83	Z25
3	0.67	P40
4	0.67	S40
5	0.46	P25
6	0.45	Z15
7	0.31	Z60
8	0.27	P60
9	0.27	S25
10	0.26	Z5
11	0.21	S60
12	0.20	S5
13	0.19	P15
14	0.13	S15
15	0.11	P5
16	0.05	L5
17	0.05	L15
18	0.03	L25
19	0.02	C
20	0.006	L40
21	0.004	L60

3-2. Economic Evaluation

To evaluate the economic aspect of the mixture designs, the cost of each material used in the sample production was first estimated based on the current market prices in the country (at the time of production). Using these estimates, the total cost of materials for one cubic meter of each sample was calculated. Table (9) shows the final material cost of the control sample, and Tables (10) to (13) present sample calculations of the material costs for mixtures Z40, P15, S60, and L25. The material costs for all mixture designs are also illustrated in Figure (1).

Table (9): Calculation of Material Cost per Cubic Meter of the Control Sample

Price of One Cubic Meter of Concrete (Toman)	Total Price of Each Material (Toman)	Unit Price of Material (Toman)	Quantity	Type of Material Used
11,183,960	11,000,000	20,000	550	Cement (kg)
	182,860	120	1524	Sand (kg)
	0	0	0	Substitute materials (kg)
	0	75000	0	Superplasticizer (g)
	1,100	5	220	Water (liters)

Table (10): Calculation of Material Cost per Cubic Meter of Concrete from Mixture Design P15

Price per cubic meter (Toman	Total price of each material (Toman)	Unit price of materials (Toman)	Quantity	Type of materials used
9,760,387	9,350,000	20,000	468	Cement (kg)
	178,287	120	1486	Sand (kg)
	99,000	1,200	83	Pumice (kg)
	132000	75,000	1.76	Superplasticizer (liters
	1,100	5	220	Water (liters)

Table (11): Calculation of Material Cost per Cubic Meter of Concrete from Mixture Design Z40

Price of One Cubic Meter of Concrete (Toman)	Total Price of Each Material (Toman)	Unit Price of Material (Toman)	Quantity	Type of materials used
7,577,636	6,600,000	20,000	330	Cement (kg)
	171,036	120	1425	Sand (kg)
	198,000	900	220	Zeolite (kg)
	607,500	75,000	8.1	Superplasticizer (liters)
	1,100	5	220	Water (liters)

Table (12): Calculation of Material Cost per Cubic Meter of Concrete from Mixture Design L25

Price of One Cubic Meter of Concrete (Toman)	Total Price of Each Material (Toman)	Unit Price of Material (Toman)	Quantity	Type of Material Used
8,521,049	8,250,000	20,000	413	Cement (kg)
	177,449	120	1479	Sand (kg)
	75,625	550	138	پودر سنگ (کیلوگرم)
	16,875	75,000	0.2	فوق روانساز(لیتر)
	1,100	5	220	Water (liters)

Table (13): Calculation of Material Cost per Cubic Meter of Concrete from Mixture Design S60

Price of One Cubic Meter of Concrete (Toman)	Total Price of Each Material (Toman)	Unit Price of Material (Toman)	Quantity	Type of Material Used
5,110,062	4,400,000	20,000	220	Cement (kg)
	176,462	120	1471	Sand (kg)
	330,000	1,000	330	Slag (kilograms)
	202,500	75,000	3	Superplasticizer (liters)
	1,100	5	220	Water (liters)

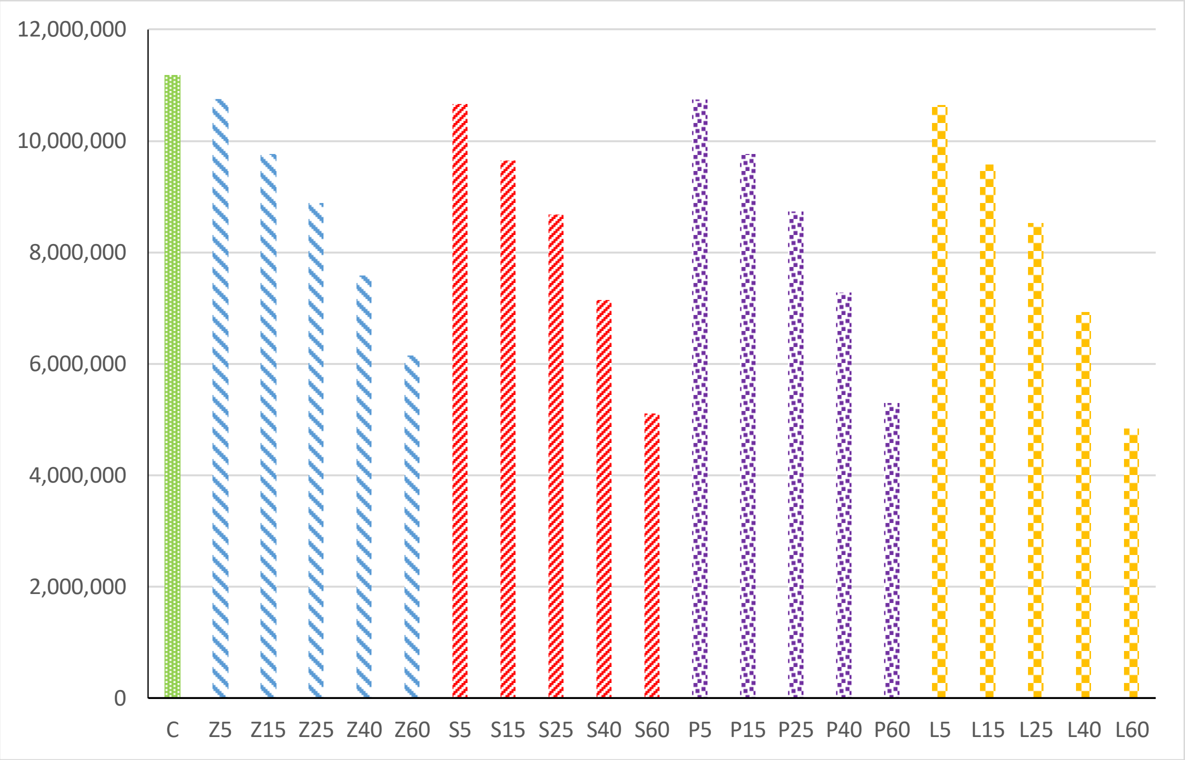

Figure (1): Material Cost per Cubic Meter of the Research Mixtures (in Tomans)

As shown in Figure (1), the highest production cost is related to the control sample, while the lowest cost corresponds to the 60% powder replacement mixture. According to the results presented in Table (14), the control mixture is considered the least desirable — or more accurately, the least economically beneficial — as it has the lowest economic desirability index.

It should be noted that, since cost is a variable where lower values are more desirable, the desirability index has been calculated using Equation (2).

The high cost of the control sample is primarily due to the high price of cement compared to the alternative materials. As previously discussed, calcium aluminate cement is significantly more expensive than Portland cement. Therefore, replacing it with industrial by-products or mineral materials — which are considerably cheaper — has had a substantial effect on reducing the final cost of the product. A comparison of the mixtures made with replacement materials to the control sample shows a cost reduction ranging from approximately **5% to 57%**.

Obviously, cost reduction alone — without considering technical (and even environmental) aspects — is not acceptable. Therefore, the aim of this part of the study is to identify the optimal mixture design by considering all three aspects: **technical**, **economic**, and **environmental**.

The results indicate that the mixtures with 60% replacement are clearly much cheaper than other designs. However, since in most technical tests, the Z40, P40, and S40 mixtures demonstrated the best performance, it is logical to focus more on the cost reduction achieved in these three. The cost reductions due to replacement in these mixtures were **36%**, **35%**, and **32%**, respectively. This level of cost reduction (around one-third), when combined with significant improvements in mechanical properties and durability, can be considered a remarkable achievement.

Table (14): Economic Desirability Index of the Mixture Designs

Economic Utility Coefficient	Minimum	Maximum	Total Cost (Toman per cubic meter)	Sample Code
0.01	4,833,249	11,184,077	11,184,077	C
0.07			10,724,169	Z5
0.23			9,727,660	Z15
0.36			8,883,025	Z25
0.57			7,577,636	Z40
0.79			6,143,367	Z60
0.08			10,658,373	S5
0.24			9,648,396	S15
0.39			8,681,544	S25
0.64			7,139,391	S40
0.96			5,110,062	S60
0.08			10,663,578	P5
0.23			9,722,137	P15
0.39			8,730,071	P25
0.61			7,278,535	P40
0.93			5,298,152	P60
0.08			10,645,774	L5
0.25			9,574,974	L15
0.42			8,521,049	L25
0.67			6,926,099	L40
1.00			4,833,249	L60

4. Conclusion:

In this study, 21 mixture designs were prepared by partially replacing calcium aluminate cement with various alternative materials at different percentages. The goal was to identify the best mixture designs in terms of mechanical properties, durability, and production cost. Since the number of variables exceeded one item, the desirability function was used for optimization and ranking. The results showed that:

1. The technical desirability index of the mixture designs was obtained considering six factors related to mechanical properties and durability simultaneously. From this perspective, the best mixture designs were Z25, Z40, and P40.
2. The least desirable designs from the technical point of view were L60, L40, and the control sample (C).
3. Economically, based on the final production cost, the most desirable mixture designs were L60, Z40, and S40, respectively.
4. The least desirable designs in terms of cost were S5, Z25, and the control sample (C).
5. This prioritization helps engineers select the appropriate mixture design based on their expectations of calcium aluminate cement and the priority of project criteria.

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The Role of Robots and Smart Technologies in Industrial Building Architecture

Dr. Mohsen Vafamehr; Seyed Arad Moeini Tabatabaei; Shiva Farivar

DOI:

PhD Candidate in Architecture, Faculty of Art and Architecture, Islamic Azad University, Mashhad Branch.

*** Corresponding author:** tabatabaeearad@gmail.com

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ABSTRACT

The construction industry has always been one of the most challenging engineering fields, which in recent decades has faced issues such as resource wastage, reduced productivity, unstable quality, heavy reliance on manual labor, and weak safety standards. Concurrent with the expansion of new technologies like robotics, digitalization, and intelligent systems, an opportunity has emerged for this traditional industry to move toward purposeful and technological industrialization. This article aims to examine the role of robots and intelligent systems in the transformation from design, construction to execution and operation of various buildings. It analyzes their functions in smart building construction and management, sensing and control systems, and explores the possibility of localizing these technologies in Iran. The research adopts a descriptive-analytical approach and utilizes specialized Persian and English sources. Findings indicate that the synergy between robotics, information technology, and industrial design provides a suitable platform to overcome the limitations of conventional and outdated construction models and paves the way for the creation of intelligent, safe, fast, flexible architecture based on sustainable development in an architectural manner.

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1. Introduction

Currently, the building construction industry in Iran faces crises such as unstable quality, extensive energy waste, material loss, high dependence on manual labor, and structural weaknesses in execution standards. Meanwhile, in developed countries, the transition from traditional and outdated methods to industrial, prefabricated, and digital models has not only reduced costs and waste but also enhanced safety, quality, and accelerated the construction process.

Contemporary Iranian architecture also requires a conceptual redefinition to respond to technological advances and the new complexities of urban structures, where design, execution, and technology are integrated seamlessly. In this context, robots and intelligent systems are recognized not only as mechanical tools but also as key facilitators in optimizing resources, improving quality and speed in construction and execution, and creating high-quality environments.

The aim of this article is to present the capabilities of new technologies in the building construction industry, with a special focus on 3D printers and construction robots, control systems and sensors, prefabricated structure fabrication, and smart technologies for the operation phase. Figure 1 illustrates an example of the necessities of "industrial building architecture" as one of the foundational pillars of today’s architectural transformation.

Figure 1 : Industrial Construction: A Necessity for Contemporary Architecture

2. Research Background

Global transformations in the construction industry—particularly within the framework of the Fourth Industrial Revolution—have paved the way for the integration of digital, automated, and smart technologies into building projects. Countries such as Japan, Germany, China, and the

United States have taken the lead in utilizing construction robots, 3D printers, off-site construction systems, and intelligent building management systems.

Scientific and technical sources categorize construction robots into three main groups:

1. **Remotely Controlled Robots:** Employed in hazardous or hard-to-reach environments.
2. **Programmed Robots:** Used for repetitive, high-precision tasks such as concrete pouring and steel placement.
3. **Intelligent Robots:** Capable of learning, environmental analysis, and real-time decision-making.

In examining innovative construction approaches, **industrial building architecture** and **off-site construction** are recognized as fundamental to transformative development. Systems like **Thermomur**, which rely on lightweight, modular, and heat-resistant components, have proven effective in reducing construction costs and accelerating timelines.

International studies, including those by *Mardani et al.* and *Esmaeili et al.*, emphasize the effectiveness of models such as **Lean Construction**, **Design for Manufacture and Assembly (DfMA)**, and **Building Information Modeling (BIM)** in establishing a systematic link between design, construction, and operation phases. These models demonstrate that integrating architecture with advanced technologies can drive the construction process toward intelligence, efficiency, and structural adaptability.

3. Findings and Analysis

3.1 Application of Robots in Construction

Robots in modern building construction are used not merely as replacements for human labor, but as **precise, repeatable, and multifunctional tools**. Various types of robots are used in different phases of construction processes, including:

- **Fireproof Coating Robots:** These robots are used to apply fire-resistant materials to surfaces in high-risk projects such as hospitals, metro stations, and towers (see Figure 2).

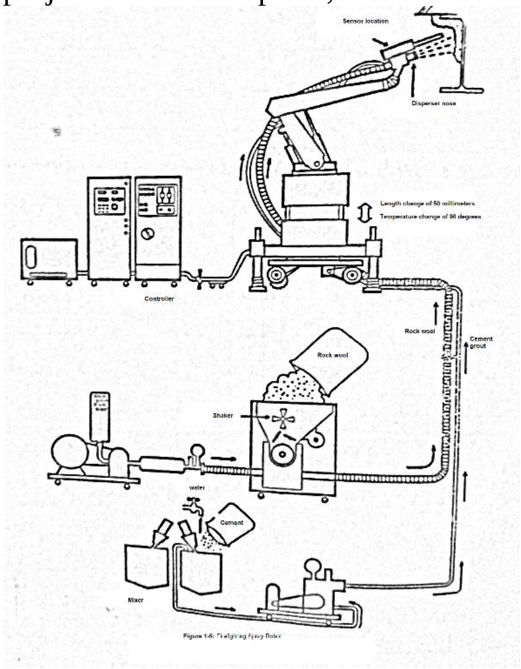


Figure 2 : Schematic Diagram of the Fireproofing System

Rebar Placement and Steel-Installing Robots: These robots, through precise programming, can accurately position rebar and securely connect them using various methods, ensuring high speed and safety during the process.

Shotcrete Robots (Concrete Spraying Robots): Utilizing guided spraying systems, these robots enable uniform and controlled concrete application on walls and formworks, significantly reducing the need for human operators (**see Figure 3**).

Figure 3 : Shotcrete Robot Equipped with Guided Spraying Systems

Plastering and Tiling Robots: Equipped with articulated arms and laser leveling systems, these robots perform precise leveling, adhesive application, and installation of stone, ceramic, and tiles with high accuracy (**see Figure 4**).

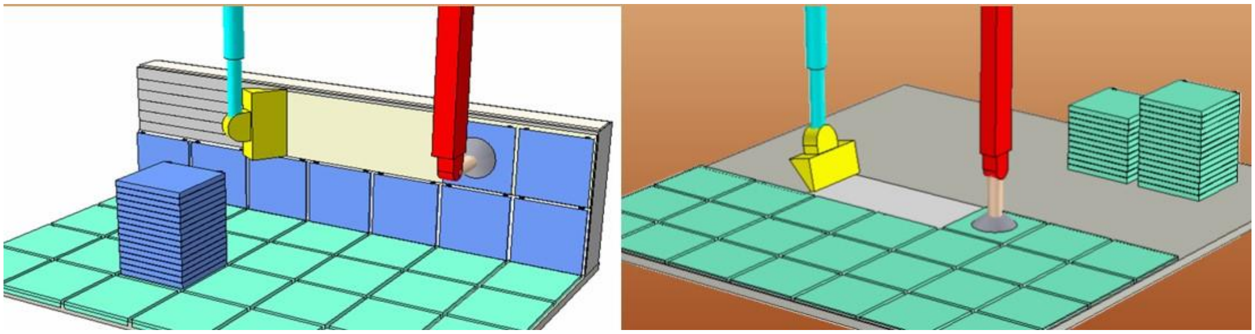


Figure 4 : Automated Wall and Floor Tiling Robot

Painting Robots: Utilizing precise nozzles and surface scanning algorithms, these robots can perform uniform paint spraying or apply any type of design and poster images on walls at high speed—eliminating the need for ladders or scaffolding (**see Figure 5**).

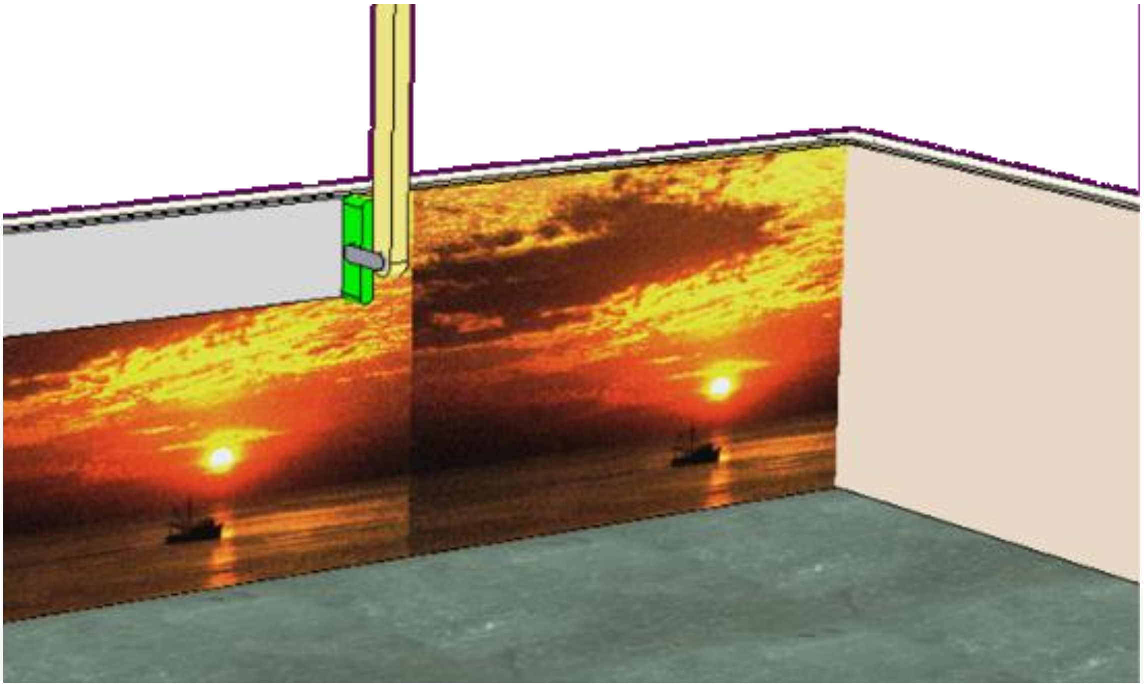


Figure 5 : Automated Painting Robot with Injection Technology

Inspection and Quality Control Robots: Equipped with optical, thermal, and magnetic sensors, these robots are capable of detecting defects, inspecting weld quality and surface cracks, monitoring gas pipes, and checking sewage systems. These robots not only accelerate the execution process but also enhance safety by reducing human involvement and significantly improve the uniformity and final quality of work (**see Figure 6**).

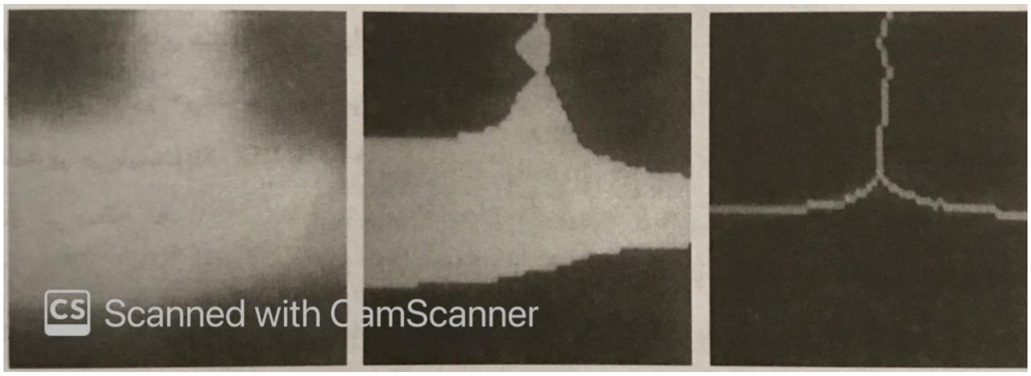


Figure 6 : Robot Vision: Raw Data and Progressive Interpretation of Cross-Reinforced Rebars

The use of these technologies is particularly efficient and effective in large-scale construction projects, harsh environmental conditions, or confined and hazardous spaces. **Figure 7** illustrates part of the application of robots in the construction and execution of cradle (arched) roofs and high-value traditional architectural structures using common building materials.

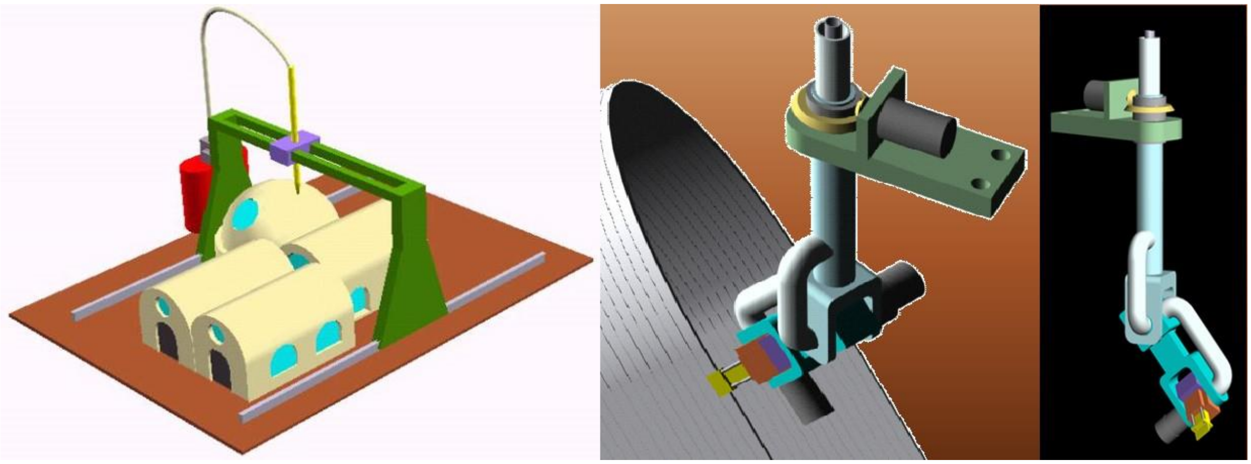


Figure 7 : Robot for Constructing Cradle (Arched) Roofs and a Robot for Building Traditional Houses Using Traditional Materials

3.2 Motion and Control Systems

In construction robots, motion systems operating along the x, y, and z axes serve as the main components determining maneuverability, precision, and accessibility. These systems shape and build various surfaces and volumes (**see Figure 8**).

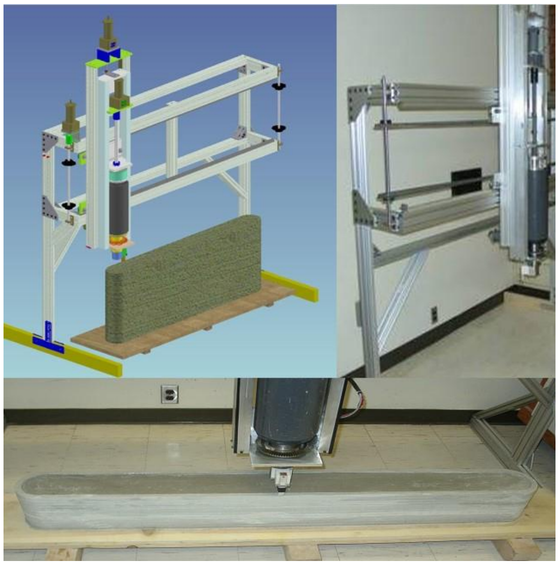


Figure 8 : Example of a Robot Capable of Constructing a Wall: One Robot Builds the Wall and Covers its Exterior with Mortar or Concrete, Then It Can Also Fill the Interior Volume with Concrete.

These systems are classified into four main groups:

1. **Wheeled:** Used for flat and extensive surfaces such as flooring and transporting equipment in mass construction projects.
2. **Articulated Arm:** Used for precise and localized operations such as welding, painting, or spot concrete pouring.
3. **Rail or Cable:** Designed for longitudinal movement along tall walls or façades.
4. **Hybrid or Mobile Platform:** Like robotic arms that provide simultaneous multi-directional and height mobility (**see Figure 9**).

Figure 9 : Various Examples of Robots with Different Movements

From a control perspective, control levels are divided into four categories:

1. **Abstraction Level:** Defining general tasks
2. **Manipulation Level:** Operational commands
3. **Servo Level:** Fine-tuning of motion
4. **End Effector Level:** Final application of tools such as grippers, nozzles, or executing arms

These control levels are designed hierarchically to provide an organized and integrated mechanism, from high-level decision-making down to precise low-level execution.

Alongside this structure, sensor systems play a vital role in environmental data acquisition and performance adjustment. Optical sensors such as **LIDAR**, magnetic photocells (for detecting the position of metals or cables), and **machine vision cameras** are among the most commonly used sensors in construction robots. By processing environmental data, these sensors enable robots to automatically respond to obstacles, material locations, surface conditions, and even potential hazards.

The combination of these motion and control systems paves the way for the development of robots capable of real-time decision-making, operational flexibility, and high precision in unpredictable construction environments.

In the transition from conventional and traditional construction to industrial architecture, technological and architectural construction, a precise understanding of robot classifications and analysis of their roles in the construction process is the first step. Construction robots are defined in three main groups according to their level of intelligence and performance:

a) **Group One:** Remotely controlled robots used in hazardous or difficult environments (e.g., disaster zones, high elevations, tunnels). Human operators control these robots from a safe distance to carry out tasks such as demolition, material removal, or initial stabilization.

b) **Group Two:** Programmed robots precisely designed to perform repetitive tasks such as concrete pouring, painting, steel placement, tiling, and plastering. These robots play a significant role in optimizing material consumption, ensuring uniform execution, and reducing human errors.

c) **Group Three:** Intelligent robots with learning capabilities, environmental recognition, automatic response to changes, and real-time decision-making. These robots utilize optical, magnetic, thermal sensors, and machine vision systems to control parameters like material density, surface leveling, and uniform distribution of materials during execution.

Within modern construction technologies, the **3D gantry construction printer** is one of the most prominent systems. Utilizing XYZ motion paths, a movable head, and a material extrusion nozzle, it can build different parts of a structure layer by layer. This 3D printing machine includes units such as the **printing head**, **material mixing and pumping unit**, **digital control center**, and **operator and worker monitoring station**. This setup simultaneously allows operators to adjust speed, layer thickness, spray direction, and emergency stops (**see Figure 10**).

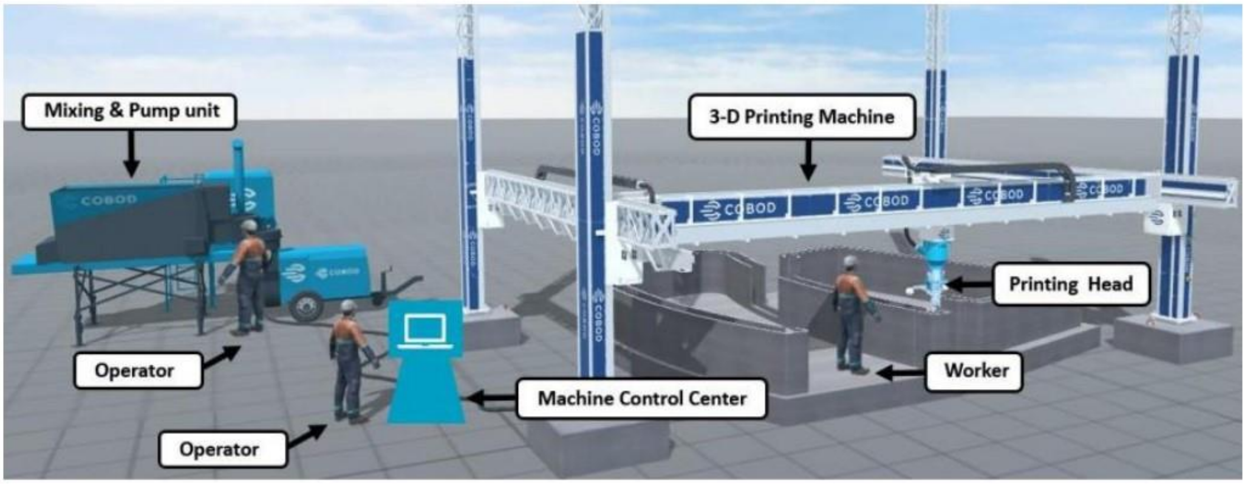


Figure 10 : Components of the Gantry 3D Printer

Analysis of this digital construction model shows that the complete execution of a structure from floor to ceiling requires adherence to a specific sequence of construction stages:

1. Printing the initial base (foundation or subfloor layer)
2. Gradual, layered construction of side walls

3. Internal connection of components (passing pipes, ducts, cables)
4. Printing the roof covering and final areas

This process, defined as **integrated on-site construction**, offers multiple advantages including reduced construction time, centralized quality control, and elimination of human errors in formwork processes.

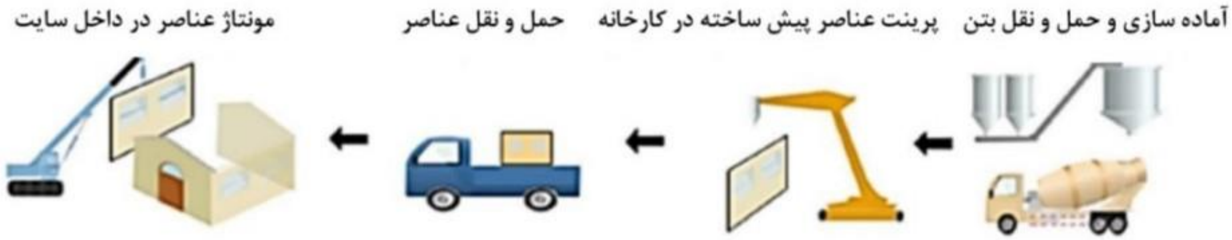
Alongside this model, two other approaches in 3D building printing have emerged:

1. Production of prefabricated parts in factories and transporting them to the construction site
2. On-site construction of modular formwork components and manual or robotic assembly

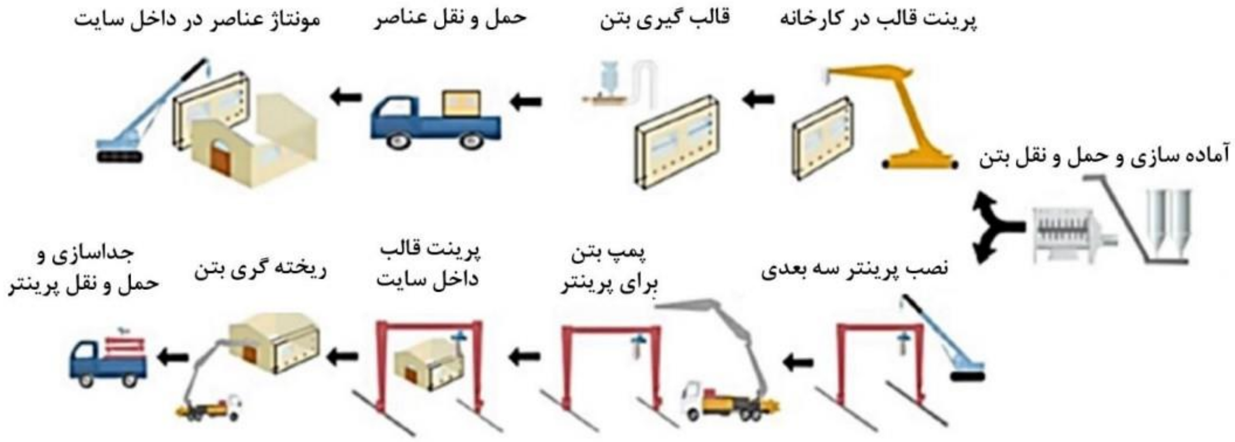
In **Table 1**, different types of printers and these three methods are analyzed in terms of cost, speed, labor, quality, and adaptability. It shows that the third method (integrated on-site building construction and execution) holds a higher competitive advantage in specific, large-scale projects.

Table 1 – Comparison of Three Types of Large-Scale Concrete 3D Printing Methods

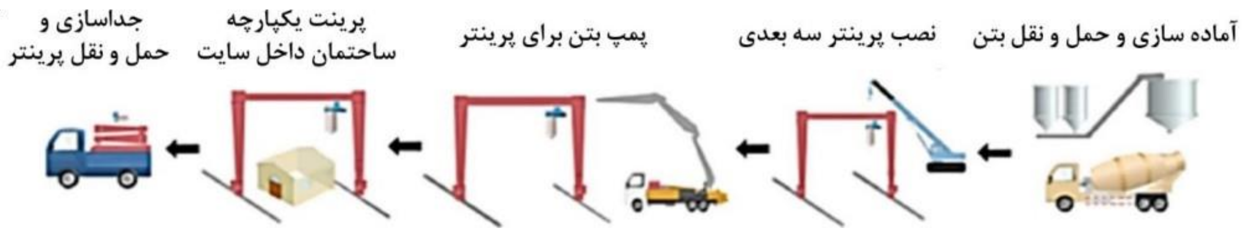
a) 3D Printing of Prefabricated Elements:



b) 3D Printing of Prefabricated Molds:



c) Integrated 3D Printing of Buildings:



Another notable advancement in this field is the integration of Building Information Modeling (BIM) systems with the Robot Operating System (ROS). This combination creates a platform for real-time control of robot operations, collision avoidance, path adjustment, and decision-making based on project data. Such a structure enables self-regulation and precise execution in the construction process while reducing dependence on human intervention.

At the same time, the role of humans in these systems must be acknowledged. Although robots handle a large portion of the execution process, human operators still play a crucial role in initial planning, sensitive adjustments, error control, exception management, and decision-making in critical situations. Therefore, the digital construction model should be viewed as a combination of advanced automation and targeted human intervention, which synergistically enhances the system's performance (see Figure 11).

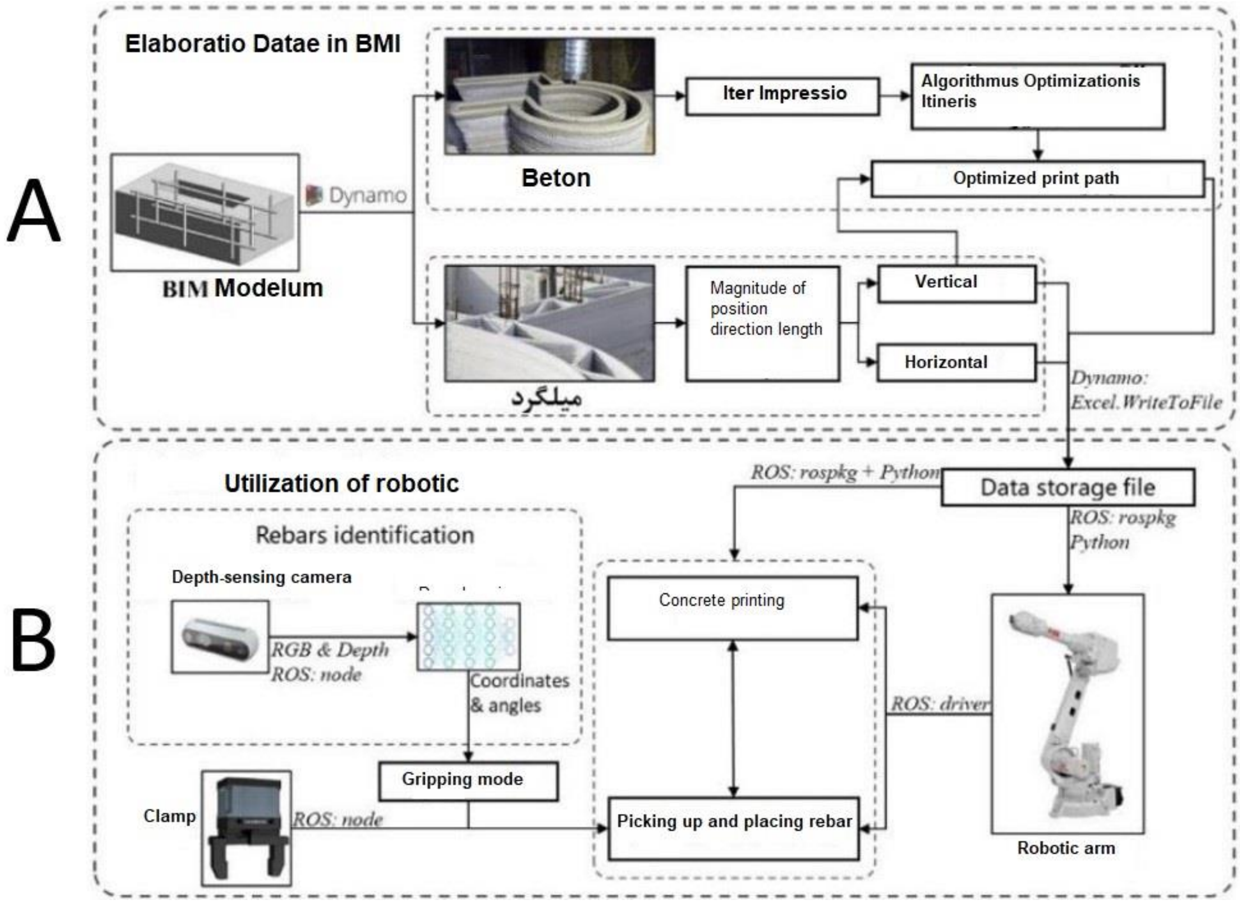


Figure (11): Robot Control System Equipped with BIM for Automatic Integration between Reinforcement Bars and 3D Concrete Printing

3-3. Smartization and Operation

In the building operation phase, intelligent Building Management Systems (BMS) play a key role in monitoring and controlling environmental conditions. These systems, connected to the Internet of Things (IoT) network and using sensors for temperature, light, humidity, presence, and motion, enable simultaneous and real-time management of various building components. With the help of machine learning algorithms, BMS can analyze occupant behavior patterns and environmental conditions and automatically adjust heating, cooling, ventilation, lighting, and security systems.

Smartization also reduces energy consumption, increases system efficiency, prevents human errors, and optimizes equipment operation. One of the advanced features of these systems is the ability to provide proactive alerts when facing technical faults or potential incidents. For example, in case of gas leakage or unauthorized temperature rise, the system automatically activates ventilation or sends a warning message to the control center.

In large projects, connecting BMS to central Smart City platforms allows environmental data to be collected and analyzed on a city-wide scale, enabling macro-level policy-making in energy, transportation, and urban safety. This approach transforms a building from an isolated unit into a part of an intelligent urban ecosystem.

3-4. Advantages of Industrial Construction

Industrial construction based on new technologies such as robotics, 3D printing, and modularization is recognized as a fundamental approach to improving construction project performance. The most important advantages of this method include:

1. **Significant reduction in execution time:** The use of prefabricated components and multipurpose robots speeds up the construction process by over 50% compared to traditional methods.
2. **Optimization of human and financial resources:** The need for unskilled labor decreases, and costs due to human error, rework, and maintenance are drastically reduced.
3. **Improved construction quality:** By precisely controlling production and installation in standardized environments, the final quality is more uniform and compliant with technical specifications.
4. **Increased site safety:** Reduced human traffic, elimination of risky activities such as working at heights or carrying heavy loads, and the use of precise robots minimize accident risks.
5. **Ability to operate in special conditions:** Industrial construction technology enables projects to be executed in remote areas, harsh climates, and even disaster zones.
6. **Environmental sustainability:** Due to optimal material usage, waste reduction, and elimination of unnecessary activities, the environmental impact of projects is significantly reduced.

Overall, using robots and automated systems in industrial building construction not only enhances productivity but also lays the foundation for a transition towards technological architecture and sustainable development in the construction industry.

Figure (12) Diagram, titled “Integrated Advanced Industrial Construction Model: From Fundamental Research to Large-Scale Rapid Construction,” symbolizes the three-layer integration of Fundamental Research, Technology Thrusts, and Technology Demonstrations in digital architecture and intelligent construction and execution.

This diagram conceptually outlines an integrated framework where research achievements in areas such as Composite Materials, Dynamic Modeling and Control, 4D Modeling and Visualization, and Multi-Robot Coordination lead to targeted industrial design, ultimately resulting in rapid, precise, and adaptable construction through technologies like construction robots, 3D printing, and Integrated Software Systems.

The proposed model contrasts with conventional construction methods, which largely rely on unskilled human labor, material waste, and trial-and-error cycles. Here, relying on synergy among parametric design algorithms, Building Information Modeling (BIM), Real-Time Inspection systems, and Workflow & Logistics Planning, the construction process becomes an intelligent, scheduled chain.

Also, the upper part of the diagram, focusing on the slogan "A House in a Day," shows that achieving such a goal is not solely a technological matter but requires coordination among economic, environmental, social, regulatory, and architectural impacts. This model, as a strategic framework for future construction and execution, demands effective collaboration among academia, industry, and regulatory bodies.

Ultimately, building a house in a day is not just an engineering idealism but an achievable goal through systematic convergence of knowledge, technology, and implementation; a paradigm that can revolutionize construction nationally and even for extraterrestrial construction.

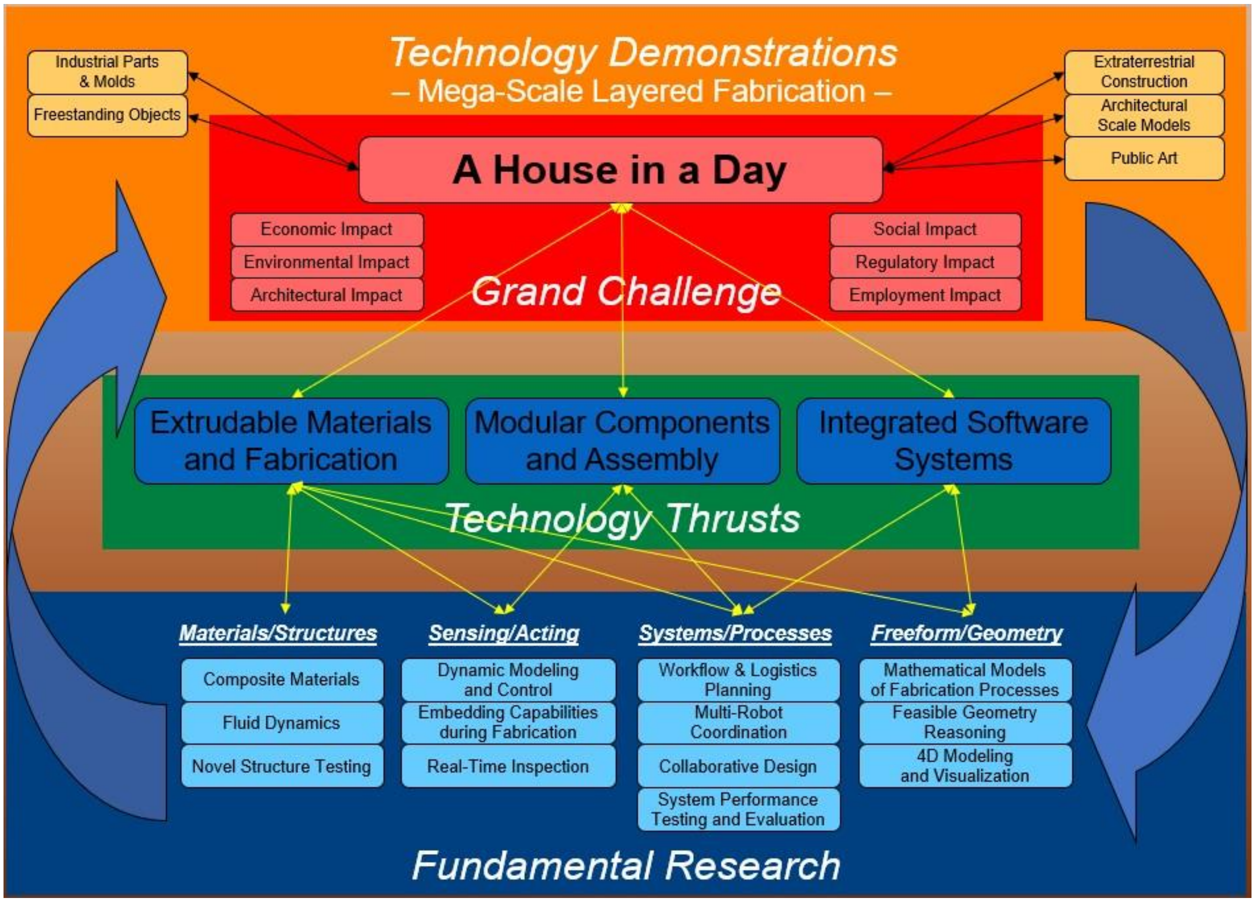


Figure (12): Rapid Industrial Construction and Technological Architecture: The Concept of "A House in a Day"

3-5. Challenges of Localization

Localizing modern construction technologies, including robotics and intelligent systems, is a complex and multifaceted process that requires careful adaptation to the social, cultural, climatic, and economic contexts of each country. In Iran, this process faces challenges such as climatic variations across different regions, diversity in construction practices between urban and rural areas, limited access to technological equipment and components, and a lack of specialized training.

From a climatic perspective, designing robotic systems to operate in the extreme heat of the south, the dry cold of the northwest, or the high humidity of the northern coasts requires special calibration and component reinforcement. On the other hand, the prevailing construction culture, which is still largely based on non-engineered and experience-based methods, is not yet aligned with the adoption of automated and smart technologies. This cultural gap must be bridged through education, the promotion of successful technological applications, and policy reform.

In terms of human resources, a shortage of skilled operators for robots, BMS data analysts, and technicians for assembling advanced equipment presents a major obstacle to the successful implementation of these technologies. Additionally, the absence of localized technical standards and codes for the design, installation, and operation of such systems leads to inconsistency in implementation and weak institutional acceptance.

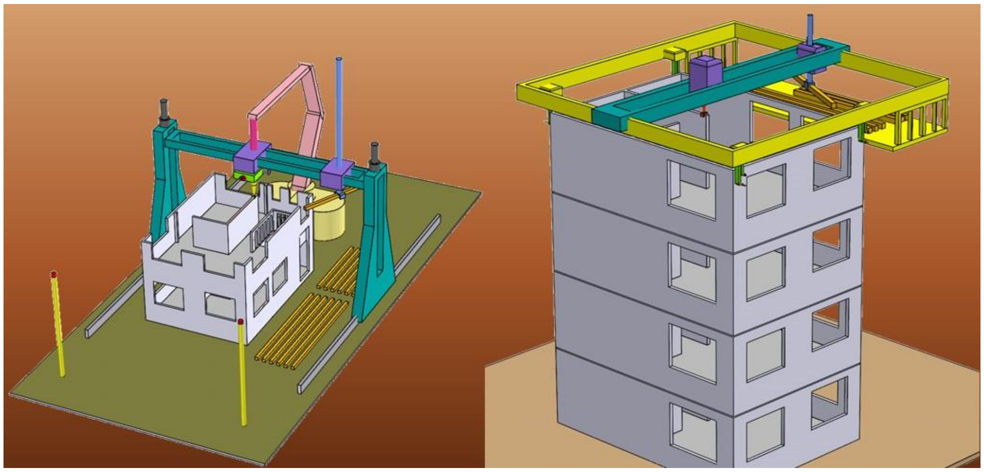
To overcome these challenges, it is recommended that alongside technological development, educational institutions, policymakers, and industry stakeholders develop programs to promote a technology-oriented culture, invest in infrastructure, train specialized personnel, and draft national standards tailored to the country’s local capacities.

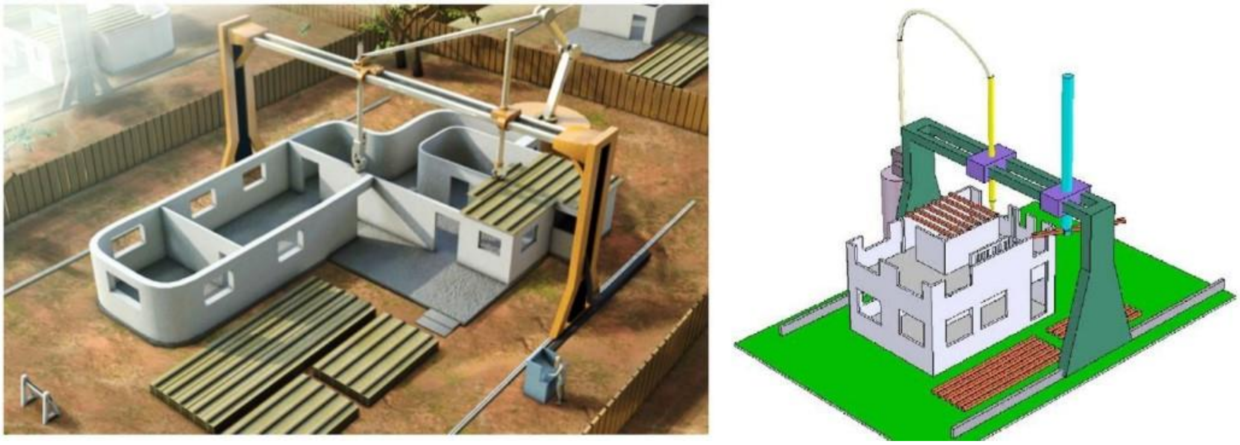
3-6. Comparative Analysis with Global Examples

In Japan, companies such as *Shimizu* and *Obayashi* employ robots for welding and transporting steel structures. Germany utilizes articulated smart arms in tunnel construction and heavy concrete work. In China, particularly in large-scale housing projects, massive 3D printers have been used to build 10 houses in under 24 hours. In all of these countries, technology has been accompanied by supportive policymaking, training, and investment, enabling practical implementation.

A comparison with Iran reveals that while scientific and research foundations are in place, the lack of investment, specialized education, and effective policymaking has hindered the practical development of such technologies.

(Figures 14 and 15) illustrate the advancements in industrial building construction and the use of robots for multi-story housing construction.





Type of cost	Share in traditional and common construction (%)	Percentage reduction using robots and automation
Labor cost	٪30	50% reduction
Material cost	٪50	20% reduction (due to execution accuracy and material waste reduction)
Financial and managerial cost	٪20	10% reduction (due to reduced execution time and rework)

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