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Methodology for Evaluating and Optimizing the Selection of Concrete Structure Demolition Methods Based on Cost, Time, and Quality (Safety)

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ABSTRACT

Nowadays, with the aging of old structures and the advancement of construction technologies, demolition projects for outdated structures have seen significant growth. this paper focuses on demolition methods in detail. In a case study conducted in Iran, this paper evaluates the demolition methods for a concrete silo using the Analytical Hierarchy Process (AHP) to select the optimal method based on cost, time, and quality (safety).

Time evaluation is performed using MSP software, while cost assessment for each method is estimated based on resources allocated to the activities within the Work Breakdown Structure (WBS) of each approach. Safety evaluation employs a combined application of the AHP and Data Envelopment Analysis (DEA) methods. Required data for constructing pairwise comparison matrices were gathered through questionnaires completed by domain experts.

The results reveal that the demolition method using concrete wire saws scores the highest among the methods evaluated. Furthermore, based on modeling results in Sap2000 software, it is shown that single-stage toppling of the silo by removing its main columns is not feasible. Subsequently, the site layout design and lifting plan calculations for the selected method were carried out.

All outcomes were compared with real-life execution, and the project's success demonstrated the effectiveness of the chosen method due to comprehensive consideration of all construction management aspects of a demolition project. This paper is written with the aim of simplifying technical concepts in the management of demolition methods.

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1. Introduction

1.1. Overview

With the aging of old structures and the advancement of modern construction technologies, the demolition of old structures has experienced significant growth. Construction management provides a comprehensive overview of all factors influencing a project, and by evaluating various criteria, it ensures the project's success. Just as construction methods are popular topics in today's construction management, demolition methods should also be given due attention. This paper focuses on selecting the optimal demolition method for two 10,000-ton concrete

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silos at the Gol Gohar Sirjan complex in Kerman Province, Iran. The objective of demolishing these silos is to access the rich iron ore reserves beneath them. The economic justification for demolishing these structures and constructing new ones is supported by the abundant iron ore reserves underneath, and the revenue generated from selling and exporting iron ore to the mine far exceeds the costs of demolition and constructing new silos. This paper addresses the management and selection of demolition methods for the silos in question, and subsequently delves into other aspects of construction management, such as designing the construction site layout plan and calculating the lifting plan. The concrete silos in question have a total height of 26 meters, an external diameter of 15 meters, and a wall thickness of 50 centimeters. Each silo has supports (columns) 7 meters in height and a 2-meter thick concrete slab roof. These silos are situated on a 23 by 35-meter, 3-meter thick, spread foundation. The primary constraints in the demolition method are the presence of a concentration and dust processing plant on the northern side and a distance of 20 meters from the edge of the main mine pit on the southern side.

1.2. Summary of the Literature and Related Studies

Extensive research has been conducted in the field of demolishing old structures. Hufbauer and Severn were among the first, in 1973 [1], to conduct various studies on the demolition of old buildings. Their research focused on the economic analysis of demolishing old buildings and replacing them with new ones, examining factors influencing the decision to demolish old buildings, such as increasing land rent, population growth, and the need for higher density. The results of this research indicate that the demolition of old structures should have an economic justification. In another study conducted by Osama Abudayyeh and his colleagues in 1988 [2], different demolition methods were evaluated in terms of efficiency, advantages, disadvantages, and implementation methods. The study also addressed how to ensure the safety of demolition projects. Similarly, Ravi Patel, in 2019 [3], conducted a brief review and comparison of demolition methods, concluding that explosion was the common method in the early demolition projects in the construction sector. Over time, demolition methods using excavators and diamond wire concrete cutting were employed in demolition projects. Assefa and Ambler, in their research in 2016 [4], investigated the decision to demolish or renovate buildings from the perspective of the life cycle environmental impacts, finding that renovation can significantly reduce environmental impacts and save resources. Furthermore, renovating buildings instead of demolishing and rebuilding can be very beneficial for areas with limited land, such as universities. Baker, Moncaster, and Al-Tabbaa's research in 2017 [5] examined the factors influencing the decision to demolish or renovate existing buildings. They argued that renovating buildings has advantages such as saving embodied energy and preserving heritage values. However, demolition can be a better solution, especially when buildings are of poor technical quality or do not comply with modern building regulations. The decision-making tools in their research include the IconCUR system, a three-dimensional tool designed by Australian researchers for decision-making in the early stages of asset management. This tool has three axes: X, Y, and Z. Axis X assesses the technical condition of the building in terms of design, maintenance, and compliance with regulations. Axis Y assesses the building's compliance with user needs, interior and exterior spaces. Finally, axis Z considers the economic, cultural, and environmental value of the building and stakeholder interests. The tool displays the results in a three-dimensional framework and suggests the best course of action for the building (such as renovation, preservation, conversion, or demolition). Regarding the demolition methods of concrete silos, very little research has been conducted. Julide Yuzbasi, in 2024 [6], conducted the most recent research on this topic, investigating the demolition of silos through one-stage overturning by removing some of the main columns using explosives. Additionally, Xieping Huang and his colleagues [7], in 2024, examined the effects of explosions on underground silos, and their results showed that the number of concrete debris ejected during the explosion would be significant. In a review study conducted by Mohsen Mohammadi and his colleagues in 2024 [8], 21 articles were evaluated based on various criteria for demolition methods, and the results are presented in the Table 1.

1.3. Innovation and Contribution of the Research to the Frontiers of Knowledge and Technology to Address Challenges and Shortcomings

This paper focuses on the comparison and evaluation of demolition methods. The findings of this research can assist construction managers in selecting the optimal demolition method by comparing and evaluating influential factors such as cost, time, and quality (safety). Today, various methods exist for demolishing concrete silos, but determining the most suitable method or combination of methods remains a subject of debate. Each method has its own set of advantages and disadvantages, and comparisons should be based on key criteria. Cost, time, and quality are the three primary criteria for method selection in the construction industry. Experts in this field believe that time, cost, and quality are recognized as the fundamental pillars of any project, and project managers strive to allocate resources appropriately and make the best

Table 1
Evaluation of demolition methods using various criteria [8]

Demolition Method		Demolition Time/Rate	Cost	Need for Skilled Operators	Safety	Environmental Pollution	Waste Reduction	Recyclability of Materials
Conventional Demolition Technologies	Manual Demolition	2	3	3	3	3	3	4
	Mechanical Demolition	4	4	4	3	3	3	3
	Implosion	5	2	5	2	2	2	2
Emerging Demolition Technologies	Static Blasting	3	3	3	4	4	3	3
	Diamond Wire Saws	4	3	4	4	2	5	5
	SCDA	3	3	2	5	2	4	4
	Hydro Demolition	4	4	4	5	2	5	5
	EDT	4	3	5	5	2	4	3
	Demolition Robots	4	3	4	4	3	4	4
	Microwave Heating	3	3	4	5	2	4	4

Extremely low = 1; Low = 2; Moderate = 3; High = 4; Extremely high = 5.

decisions to complete projects in the shortest possible time, at the lowest cost, and with the highest quality. [9], [10].

2. Research Methodology

This research is applied in nature and employs an analytical-descriptive approach. The required data was collected through a literature review. Additionally, part of our study was conducted based on project experiences and the expertise of individuals related to the research topic. Initially, based on a literature review and a review of published articles, the modeling and structural behavior during demolition in each method were examined. In each method, the parameters of cost, time, and quality (safety) were comprehensively analyzed and compared.

In the next stage, using the Analytic Hierarchy Process (AHP) method proposed by Thomas Saaty [11], which is used to solve multi-criteria decision-making problems, and with the help of the Expert Choice software, the demolition methods were compared, and the score of each method was calculated. The proposed research method in this paper for selecting the appropriate demolition method was used in a study by A.J. S´anchez-Garrido in 2022 to select modern construction methods [12].

The use of experts and their experience in multi-criteria decision-making was proposed by Z.-S. Chen in 2021 to evaluate proposals in tendering processes, which considers uncertainty and complexities in human evaluations using fuzzy tools and group decision-making methods [13]. Time assessment was performed using MSP software as suggested by researchers in this field [14]. In this method, based on the schedule obtained for each method using MSP software, to prepare a schedule, a WBS was first prepared for each demolition method, and then by defining the relationship between activities and allocating resources, the duration of activities was calculated, and the total demolition time was obtained using the above method. The basis for calculating the cost criterion is based on the resources allocated to each of the execution operations in the Work Breakdown Structure (WBS) of each method [15]. In this way, in each method, its breakdown structure is prepared, and for the broken-down activities, the required resources and costs, including materials, labor, machinery, and transportation, are allocated, and finally, the amount of execution of that activity is calculated. By summing the costs of each activity, the demolition cost of each method is calculated. Safety assessment was conducted using both AHP and DEA, and the necessary information for forming pairwise comparison matrices in these methods was collected through questionnaires from experts in the field. In the next stage, using the results of the evaluation of each item, the overall evaluation of the method was performed using the AHP method, and the method that obtained the highest score in the evaluation was selected as the optimal method.

In addition to selecting the optimal demolition method, this research also addresses the application of other aspects of construction management such as examining the site setup, designing the project site layout plan, and the role of the lifting plan in the selected method. Given the increasing trend of demolishing old structures, presenting new methods in demolition management and demolition methods

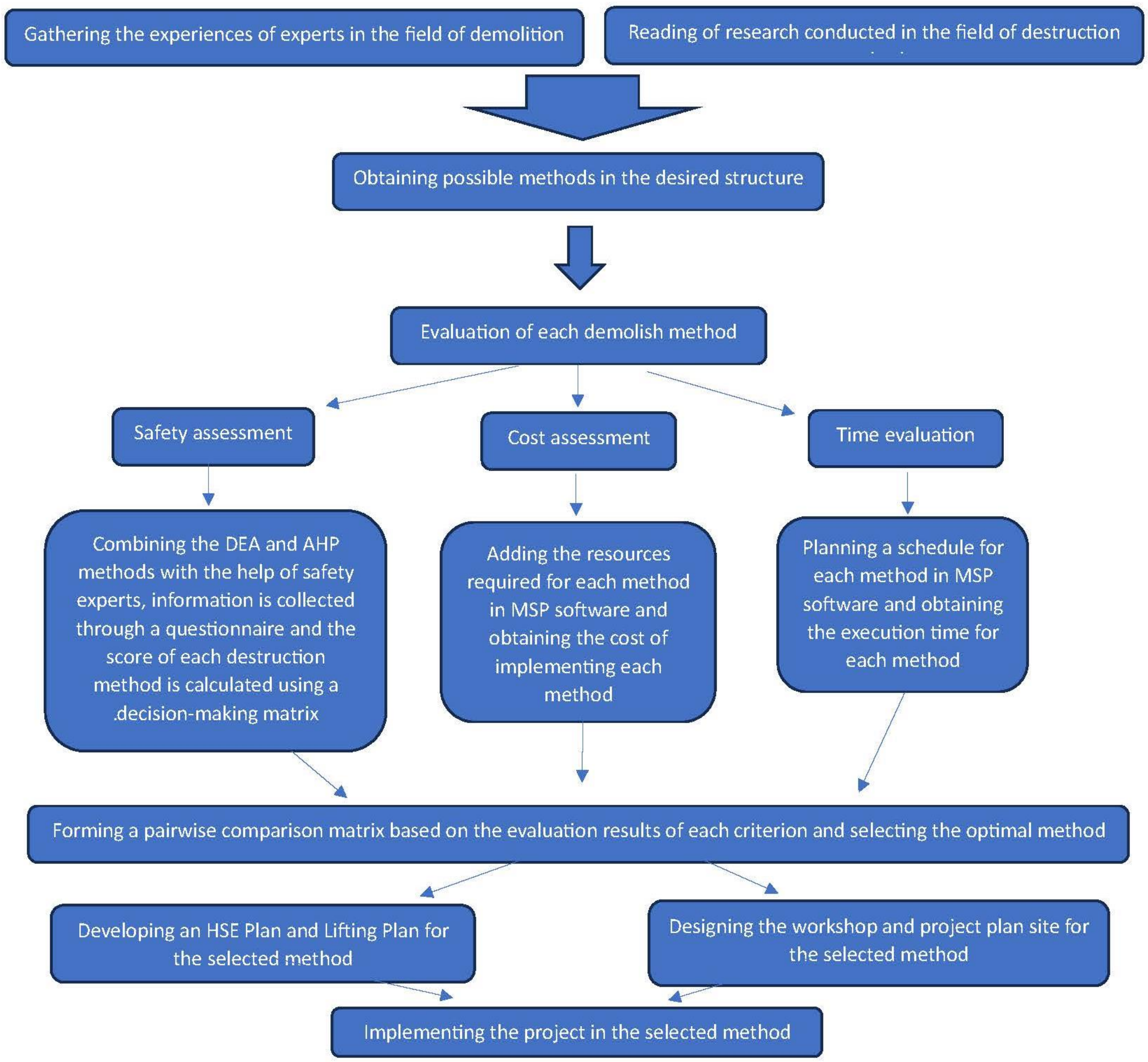


Figure 1: Research methodology and results

is of particular importance. At the end of this paper, we will address how to examine and select the demolition method of the desired structure from various perspectives and, in the next step, by entering other effective factors in site management, to achieve the most optimal project execution method. At the end of this research, the selected method in the research results is compared and validated with the reality of the implemented project case study. Also, the impact of using a suitable site layout plan design and lifting plan for the selected method on the project execution process is investigated.

The flowchart below shows the path and process of the research in this study (Figure 1).

3. Case Study

This research focuses on two 10,000-ton capacity concrete silos at the Gol Gohar Sirjan complex in Kerman Province, Iran. The objective of demolishing these silos is to access the rich iron ore reserves beneath them. This paper specifically addresses the demolition methods for these silos, and while no research has been conducted on constructing new silos, it is recommended that future studies explore and evaluate methods for building new silos.

The concrete silos in question have a total height of 26 meters, an external diameter of 15 meters, and a wall thickness of 50 centimeters. Each silo has supports (columns) 7 meters in height and a 2-meter-thick concrete slab roof. These silos are situated on a 23 by 35-meter, 3-meter thick, spread foundation. The primary constraints in the demolition method are the presence of a concentration and dust processing plant on the northern side and a distance of 20 meters from the edge of the main mine pit on the southern side.

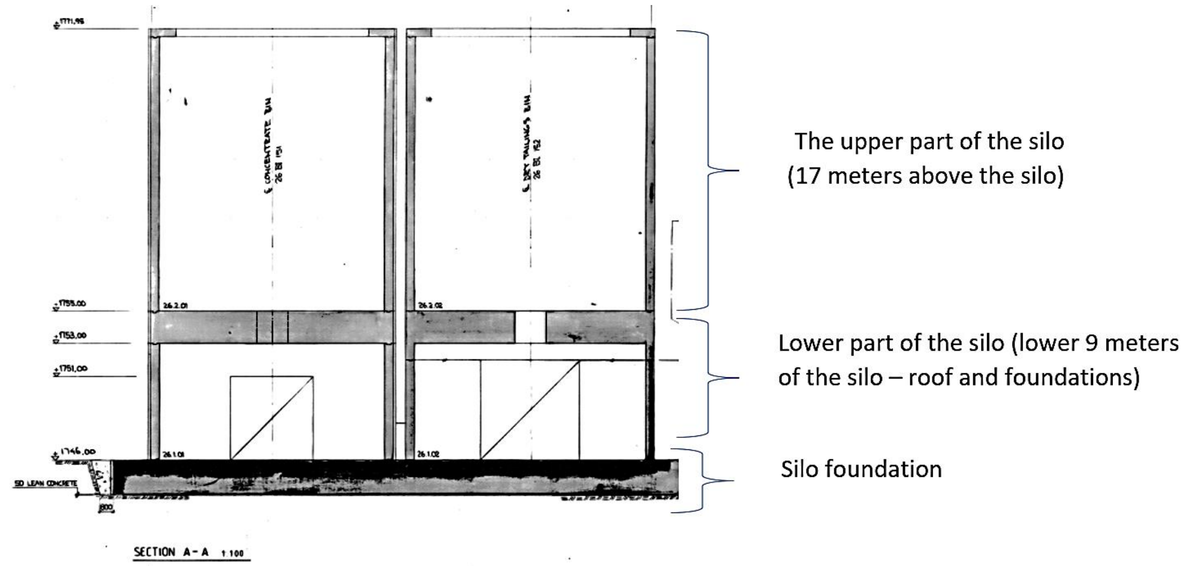


Figure 3 Silo structure division - silo cross-section in height

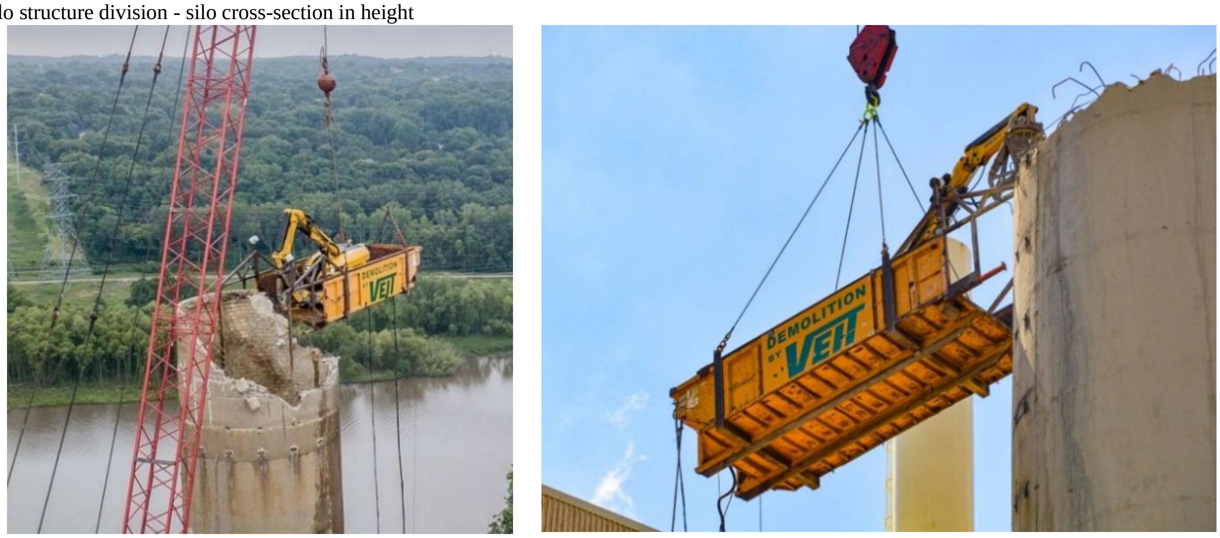


Figure 4. Transferring the shovel on a metal platform by a dry boom crane at a height for demolition by a hydraulic jaw (scissors) or a pickaxe in stages from top to bottom

In each silo demolition method, the execution steps are divided into three sections of the silo structure, as follows:

- Section 1: Demolition of the upper 17 meters, including the wall and the main body of the silo (where the minerals are stored).
- Section 2: Demolition of the 2-meter-thick roof and the 7-meter-high silo columns.
- Section 3: Demolition of the 3-meter-thick reinforced concrete foundation and 1-meter-thick lean concrete.

The feasible demolition methods for each section will be described in detail in the following sections.

Demolition Methods for the Upper Section of the Silo (17 Meters): Three methods are proposed for demolishing the upper section of the silo, which includes the main silo wall:

Method 1: Demolition using explosives: According to calculations based on Publication 410 (Technical Regulations for Explosives and Blasting in Mines) [16] and blasting demolition relationships [17], holes are drilled at 25 cm intervals around the silo and at the height of the silo using a hand hammer, following safety precautions. These holes are filled with 30-energy emulsion explosives and detonators. The silo is then demolished by a blasting team. Of the 40 cm drilled hole, 30 cm is filled with explosives and 10 cm with sealing material. In this method, using demolition engineering and designing a demolition pattern, and using time delays in detonator explosions, the silo is designed to collapse inward without posing a threat to the surrounding environment. It is worth noting that only the concrete parts of the silo are demolished using this method, and the reinforcements are bent. After the concrete part of the silo is demolished, the reinforcements are cut, and the demolition is completed in this section. At the end of each section, the rebars are separated from the demolished concrete using pneumatic hammers and air cutters and are sorted.

Method 2: Using mechanical equipment: A steel platform is constructed for placing an excavator on it. The excavator, equipped with a breaker, is lifted to a height of 25 meters using a heavy-duty crawler crane and begins to demolish the silo in stages and levels, continuing in this way until the first section of the silo is demolished. The disadvantage of this method is its time-consuming nature. In this method, the inside of the concrete silos can be filled with a mixture of soil, and the excavator can be placed inside the silo on the piled soil and gradually demolish the silo wall and move downwards.

Method 3: Demolition using diamond wire cutting: The execution of this method is carried out according to ACI Report 555 [18]. According to the attached drawings, the wall of each silo is divided into segments, each of which is a quarter of a circle, which is cut at different levels using a concrete diamond wire saw and transferred to the ground by a crane. Before starting the wire cutting process, a scaffolding platform is installed inside the silos so that the equipment can be stationed at different working levels. Two cutting machines are placed inside each silo and simultaneously cut the concrete pieces. At the end of each cut, the section of the wall is cut and transferred to the ground by a crane. The execution of the formwork, according to the design calculated, is carried out using omega (triangular) scaffolding with an arrangement that is as similar as possible to a circle inside the silo and on its roof. The dimensions at the main quadrilateral bases are 1.2 meters by 1.2 meters with a height of 1 meter, which is used for better resistance and performance. The distance between the triangular elements (square bases) is 1 meter. Due to the quarter-circle cut, the scaffolding adheres to the wall only in places where excavation is to be carried out, and in other areas, there will be a distance of about 50 centimeters from the inner edge of the wall. The weight of each cutting machine is about 350 to 400 kilograms, and its dimensions are 1 meter by 1 meter. Two machines are to be operated on each platform. Each machine has two personnel, making a total weight of about 1000 kilograms (1 ton) on the structure. According to the design of the formwork manufacturer, the load-bearing capacity of each square meter is 1 ton, and based on this, the scaffolding platform structure has sufficient strength with a high safety factor.

Demolition Methods for the Second Section of the Silo (2-meter roof and 7-meter columns)

Method 1: Demolition using explosives: In this method, according to calculations based on Publication 410 (Technical Regulations for Explosives and Blasting in Mines) and blasting demolition relationships, holes are drilled at 1-meter intervals in the roof of the silos using a hand hammer, adhering to safety precautions. These holes are drilled to a depth of 150 cm and filled with high-energy emulsion explosives and detonators. The blasting team then detonates the charges to demolish this section of the silo. Of the 150 cm drilled hole, 110 cm is filled with explosives and 40 cm with sealing material.

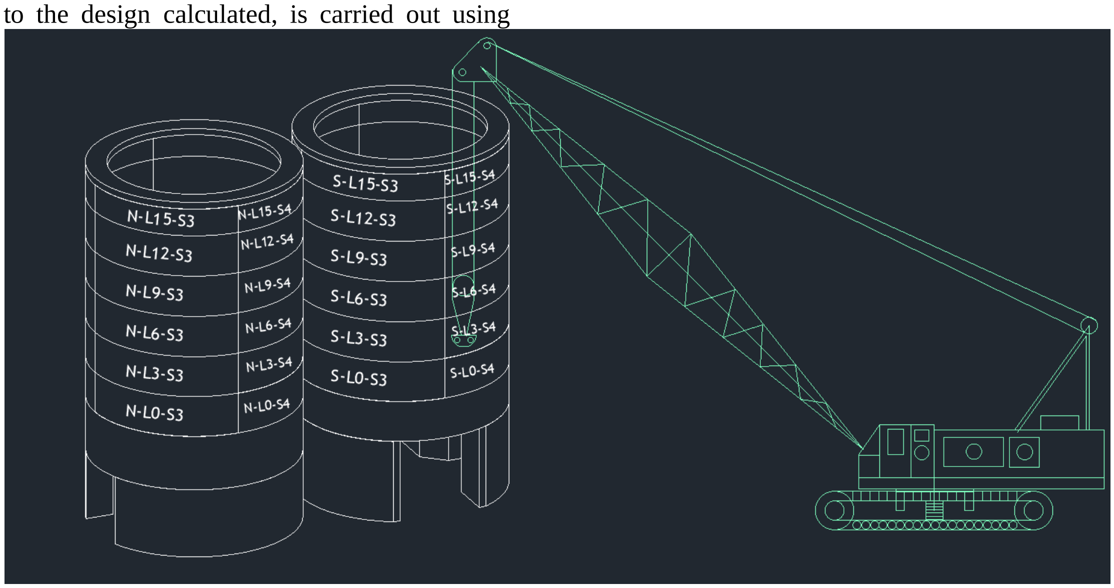


Figure 5. Deploying a crane next to the silo and transferring the cut pieces to the ground using a cutting wire.

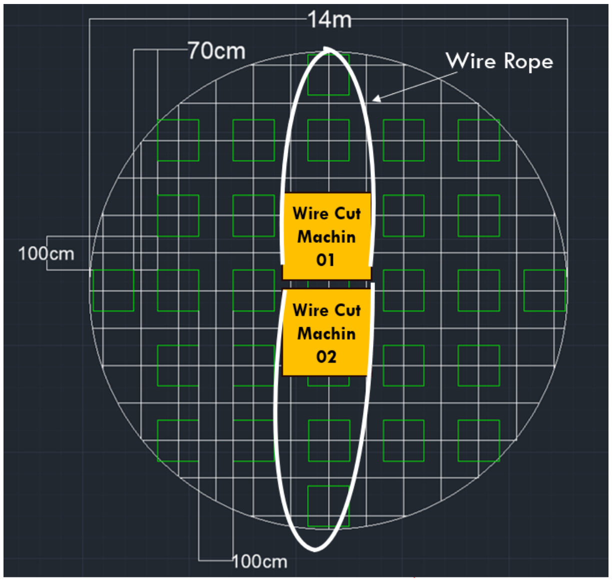


Figure 6 Structure map and cutting path of silo wall concrete

Simultaneously, in areas where the silo's columns are located, the hole depth reaches 7 meters, as the concrete in these areas extends to the ground level. Using demolition engineering and designing a specific demolition pattern, along with time delays in detonating the charges, the design ensures that the roof and columns of the silo collapse inward without endangering the surrounding area. It's important to note that only the concrete parts of the silo are demolished using this method, and the reinforcements are bent. After the concrete portion is demolished, the reinforcements are cut, and the demolition of this section is completed. At the end of each section, rebars are separated from the demolished concrete using pneumatic hammers and air cutters, and they are sorted.

Demolition Methods for the Second Section of the Silo (2-meter roof and 7-meter columns)

Method 2: Using Mechanical Equipment: This method involves using an excavator equipped with a breaker to demolish the concrete in stages. It's important to note that for demolishing the columns, there's no need for a crane, as the excavator alone can perform the demolition. However, for the roof demolition, due to its 9-meter height, the excavator must be lifted onto the roof using a crane. After the roof is demolished, the excavator is again lowered to the ground using the crane. In this method, the excavator starts demolishing from one point on the roof and moves in the opposite direction of demolition until the entire roof area is demolished.

Method 3: Using Diamond Wire Cutting: In this method, the roof is divided into 25-ton segments using drill holes. A diamond wire cutting machine is then used to divide the roof into smaller pieces, similar to the wall, and these pieces are transferred to the ground using a crane. To cut the columns, each column is cut at the junction with the foundation using a diamond wire saw, and then an external force is applied to cause it to overturn.

Demolition Methods for the Third Section of the Silo (3-meter-thick foundation)

Method 1: Demolition using explosives: In this method, according to calculations based on Publication 410 (Technical Regulations for Explosives and Blasting in Mines) and blasting demolition relationships, holes are drilled at 2-meter intervals throughout the silo foundation using a drill rig, adhering to safety precautions. These holes are drilled to a depth of 150 cm and filled with high-energy emulsion explosives and detonators. The blasting team then detonates the charges to demolish this section of the silo. Of the 150 cm drilled hole, 110 cm is filled with explosives and 40 cm with sealing material. Using demolition engineering and designing a specific demolition pattern, along with time delays in detonating the charges, the design ensures that the silo foundation collapses inward without endangering the surrounding area. It's important to note that only the concrete parts of the silo are demolished using this method, and the reinforcements are bent. After the concrete portion is demolished, the reinforcements are cut, and the demolition of this section is completed. At the end of each section, rebars are separated from the demolished concrete using pneumatic hammers and air cutters, and they are sorted.

Method 2: Using Mechanical Equipment: This method involves using an excavator equipped with a breaker to demolish the concrete in stages. It is estimated that 3 PC300 excavators will be needed to work in two shifts to keep up with the schedule.

One-step overturning of the silo by removing its columns: In this method, a portion of the silo columns is initially demolished at the lower level using an excavator or diamond wire cutting. Then, by placing explosives in the remaining columns and creating an explosion, the other columns are demolished, causing the silo to overturn due to the induced tension and failure in the opposite columns. In this method, a deep pit with dimensions 1.5 times the diameter of the silo (25 meters) must be excavated at the location where the silo is to be overturned to prevent the scattering of concrete debris during the overturning process. For the one-step overturning method, this method must first be modeled in the SAP2000 software, and the results obtained after removing the elements of some of the main columns should be followed, similar to the modeling performed by Julide Yuzbasi in her 2024 research [6]. To do this, the structure is modeled in the SAP software according to the construction drawings. The results of the modeling when two columns are removed from the four columns of the silo show that the stress experienced in the remaining two columns under dead loads and without a factor is 0.928, which means that one-step overturning of the silo by removing the columns is not possible. The figure

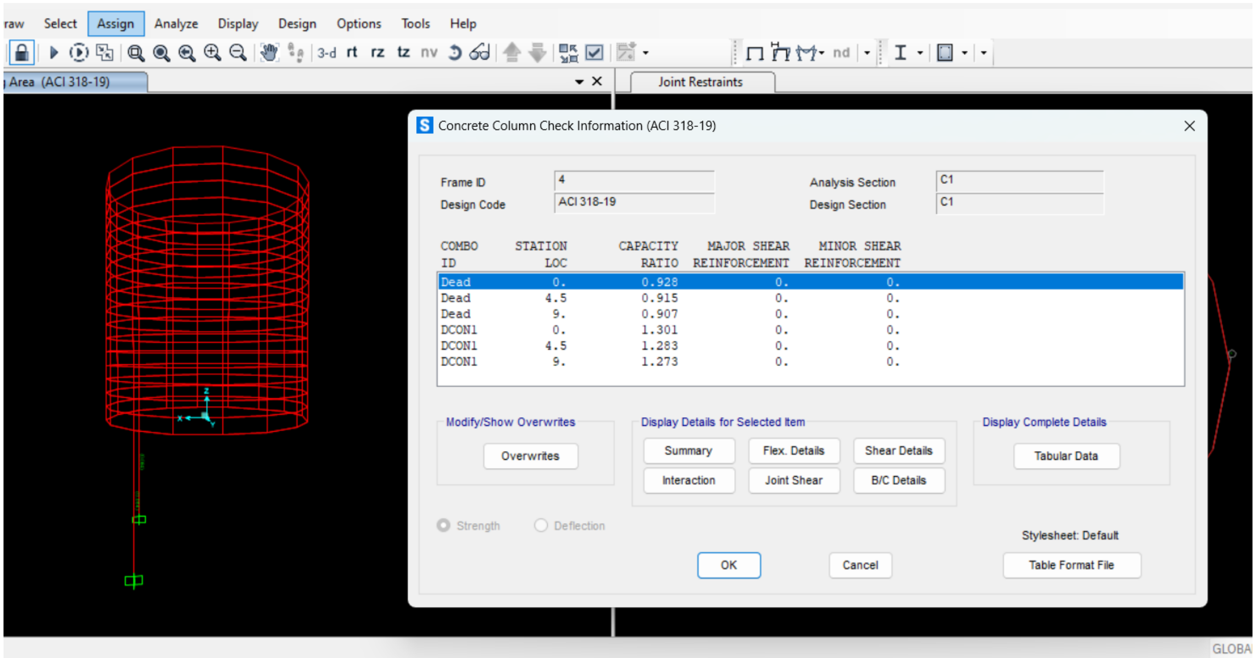


Figure 7 Silo modeling results by removing 2 columns in Sap2000

7 shows the results of modeling the silos after removing two columns, which indicates that the silo will remain stable after removing two columns.

4. Quality (Safety) Assessment

The basis for calculating quality (safety) is a combination of the AHP and DEA methods. This proposed method, recommended by Mehdi Mohajeri and Abdollah Ardashir in 2016 [19], and applied to the analysis, risk, and safety of construction, allows us to compare and score the risks of each method. The potential risks identified by HSE experts include: projection of concrete fragments during explosions, the possibility of explosions during the placement of explosives, explosions during the transportation of explosives, the projection of crushed concrete during drilling with a drill rig, the projection of crushed concrete during drilling with a core drill, breakage of the concrete cutting wire, electric shock, the projection of concrete pieces during crane lifting, the fall of an excavator from the top of the silo during demolition, breakage of the rebar cutting stone, the projection of splinters during rebar cutting, and the projection of crushed concrete during demolition by an excavator.

In the execution methods, as suggested by Mehdi Mohajeri and Abdollah Ardashir, the probability of occurrence of each of the above events is calculated using two methods, and the results from both methods are used in the risk analysis. First, the probability of occurrence is calculated using the DEA method. In this method, for each of the events mentioned in the safety assessment, the probability of occurrence is obtained based on the opinions of experts. In the second method, using the concentration factor relationship proposed by Badri and his colleagues in 2012 [20], and considering the risk factors and the level of participation of these factors in each of the safety evaluation factors of the demolition method, the probability of occurrence of each of the mentioned incidents in the safety assessment is calculated using the concentration factor formula presented below (Eq. 1).

$$C_{ij} = \frac{X_i Y_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{m} X_i Y_{ij}} \quad (1)$$

Where X_i is the number of risk factors from the incident factors (Fi) and Y_i is the weight of each risk factor that is important in the occurrence of the incident (and is estimated by experts). The Table 2 shows the ranking of risk factors for calculating the concentration factor.

Table 2.
Risk factor ranking

Num	Dangerous Factor	Grade (1-9)
F1	Inadequate management control	9
F2	Unsafe practices	6
F3	Unfavorable working conditions	7
F4	Personal factors	5

In the subsequent stage, the consequences of human injury and financial loss are evaluated based on the opinions of expert specialists. The weight of the risk level criteria, which include the probability of occurrence (using the DEA method), financial consequences, and human injury consequences, is derived from the research of

Table 3
Survey results regarding risk level

	Criteria	Throwing concrete pieces in an explosion	Possibility of explosion while placing explosives	Explosion while transporting explosives	Crushed concrete being thrown out during drilling by a drill rig	Crushed concrete being thrown out when drilling with a core drill	Concrete cutting wire breaks	Electric shock	Concrete piece thrown out while being moved by crane	Excavator falls from top of silo during demolition	Rebar cutting stone breakage	Throwing of pleats when cutting rebar	Crushed concrete being thrown out during demolition by an excavator
Probability of an accident	scarce	0	7	9	6	3	1	3	7	6	2	2	2
	Sometimes	1	2	1	3	4	1	3	3	4	3	3	5
	Possible	2	1	0	1	3	5	3	0	0	3	3	3
	Common	7	0	0	0	0	3	1	0	0	2	2	0
Life consequences	Minor damage	3	1	0	7	7	2	2	0	0	4	6	4
	Severe injury	3	1	1	3	3	3	3	1	3	3	3	6
	Permanent disability	2	2	3	0	0	3	3	3	6	2	1	0
	Death	2	6	6	0	0	2	2	6	1	1	0	0
Financial consequence	Low	1	1	0	9	8	5	6	6	0	6	8	7
	Medium	1	1	0	1	2	2	4	4	1	4	2	3
	High	3	3	4	0	0	2	0	0	3	0	0	0
	Very High	5	5	6	0	0	1	0	0	6	0	0	0

Ardeshir and colleagues. Based on this, the weight of each sub-criterion is as follows:

- Probability of occurrence: Frequent (0.1), Possible (0.05), Occasional (0.033), and Rare (0.025)
- Human injury consequences: Death (0.146), Permanent disability (0.0731), Severe injury (0.04867), and Minor injury (0.0365)
- Financial consequences: Very high (0.105), High (0.0526), Medium (0.035), and Low (0.0262) Finally, the risk of each hazard is calculated using the relationship proposed by Wang et al. in 2088 [21] for risk assessment (Eq. 2).

In this relationship, W_j represents the weight of the criteria determined by the AHP method, $s^*(H_{jk})$ is the optimal score from the determined evaluation class, and V(Ai) is the final weight of the risks. With the final weight, the risks can be ranked and prioritized.

$$V_{(A_i)} = \sum_{j=1}^{m} W_i V_{ij} = \sum_{j=1}^{m} W_i (\sum_{k=1}^{kj} s^*(H_{jk}) NE_{ijk}) \quad (2)$$

$$i = 1, \ldots, n$$

In the final stage, based on the weighted score of each of the probability of occurrence criteria (based on risk factors and concentration relationship), probability of occurrence (based on DEA), human injury consequences, and financial consequences, the potential risk of each hazard is calculated. Considering that each of the mentioned hazards is related to which demolition method, the safety assessment score of each method is calculated by the algebraic sum of the hazard scores of each related factor. As mentioned in the research methodology, to evaluate the safety of demolition methods, a combination of the AHP and DEA methods is used, along with questionnaires and opinions of safety experts. The questionnaire results regarding the probability of occurrence, human injury consequences, and financial consequences of each risk level are presented in the following table.

Table 4
Risk score for the qualities being assessed

Dangerous	risk factor concentration	Probability of an accident	Life consequences	Financial consequence	Total Grade of Dangerous
	0.14	**0.14**	**0.64**	**0.08**	
Throwing concrete pieces in an explosion	0.3	0.833	0.6937	0.744	0.662
Possibility of explosion while placing explosives	0.24	0.291	1.1074	0.744	0.843
Explosion while transporting explosives	0.23	0.258	1.144	0.8404	0.868
Crushed concrete being thrown out during drilling	0.24	0.299	0.4015	0.2708	0.354
Crushed concrete being thrown out when drilling	0.22	0.357	0.4015	0.2796	0.360
Concrete cutting wire breaks	0.25	0.608	0.7303	0.4112	0.621
Electric shock	0.22	0.424	0.7303	0.2972	0.582
Concrete piece thrown out while being moved by	0.22	0.274	1.144	0.2972	0.825
Excavator falls from top of silo during demolition	0.24	0.282	0.7306	0.8228	0.606
Rebar cutting stone breakage	0.26	0.499	0.5842	0.2972	0.503
Throwing of pleats when cutting rebar	0.26	0.499	0.4381	0.2796	0.408
Crushed concrete being thrown out during	0.25	0.365	0.438	0.2884	0.389

The numbers presented in the table above represent the number of opinions collected through the questionnaire, which was completed by 10 expert specialists in the field of safety. In the next stage, considering the weight of each criterion mentioned in the previous section, the risk scores are calculated. The table below shows the overall risk score for each risk criterion in the safety assessment. As observed, the risks associated with demolition methods using explosives and concrete cutting have higher scores compared to the demolition method using an excavator, indicating a lower safety score for demolition using these two methods.

In the subsequent stage, based on the obtained risk scores, the safety score of each method is calculated. This is done by algebraically summing the total risk scores of all related factors for each demolition method in the table above, and the safety assessment for each method is obtained. Then, by forming a pairwise comparison matrix for the safety criterion when comparing demolition methods, the first pairwise comparison matrix is constructed in the AHP method. It is worth noting that a higher risk score indicates a lower safety level of the demolition method and entails a higher risk. The table below shows the safety score of each method, and Matrix 1 displays the values of the pairwise comparison matrix for evaluating the safety of demolition methods.

Table 5
Risk score for each destruction method

Demolish Method	Total Risk Score	Safety assessment rating
Explosion	3.648	3
Demolish with Excavator	0.995	1
Wire Cut	2.393	2

$$\begin{pmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{pmatrix} = \begin{pmatrix} 1 & 0.27 & 0.65 \\ 3.66 & 1 & 2.4 \\ 1.52 & 0.42 & 1 \end{pmatrix} \quad (3)$$

$$S_{12} = \frac{1}{S_{21}}, S_{13} = \frac{1}{S_{31}}, S_{23} = \frac{1}{S_{32}}$$

Eq. (3) is Pairwise comparison matrix values of destruction methods in assessing the safety of each method.

In the above matrix, the ratios represent the safety score of the explosion method relative to the mechanical excavator method, the safety score of the explosion method relative to the concrete cutting method, and the safety score of the mechanical excavator method relative to the concrete cutting method. The diagonal of the matrix is 1 since the ratio of the safety score of each method to itself is always 1. In this matrix, the higher the value of the matrix elements, the higher the safety (lower risk score) of that method.

5. Cost and Time-Based Evaluation

The cost criterion will be calculated based on the resources allocated to each of the execution activities in the Work Breakdown Structure (WBS) of each method. For each method, its WBS is prepared, and the required resources and costs for executing the activities, including materials, manpower, machinery, and transportation, are allocated. Finally, the cost of executing that activity is calculated. By summing up the costs of each activity, the demolition cost of each method is calculated.

The time is based on the schedule obtained in each method using the MSP software. To prepare the schedule,

Table 6
Results of time and cost of implementing each method

Num	Section	Demolish Method	Time (Days)	Gross cost $	Book value of equipment and machinery after depreciation $	Net cost of Demolish $
1	Wall of Silo	Wire Cut	83	109,850 $	50,750 $	59,100 $
2		Explosion	92	126,861 $	49,263 $	77,599 $
3		Excavator	88	80,513 $	9,669 $	70,844 $
4	Roof & Column of Silo	Explosion	51	85,575 $	23,013 $	62,563 $
5		Excavator	49	49,673 $	9,669 $	40,004 $
6	Foundation	Explosion	42	79,115 $	23,328 $	55,788 $
7		Excavator	32	53,688 $	9,669 $	44,019 $

Table 7
MSP software output for silo wall demolition by explosion method

ID	ID	Task Mode	WBS	Task Name	Duration	Predecessors	تاریخ شروع	تاریخ پایان	Critical	Successors	Resource Names	Cost
0	0		0	Explosive Method Demolish for Section1	92 days		1402/12/14	1403/3/14	Yes			IRR 101,488,000,000
1	1		1	Site mobilization	14 days		1402/12/15	1403/3/14	Yes			IRR 59,888,000,000
2	2		1.1	Workshop Mobilization	7 days		1402/12/15	1402/12/21	Yes	3	Conrex[3],Container[1],Diesel	IRR 29,300,000,000
3	3		1.2	Scaffolding intire Silo	7 days	2	1402/12/22	1402/12/28	Yes	6,11	Scaffold[2],Simple worker[6],S	IRR 30,588,000,000
4	4		2	Demolish Silo	58 days		1403/2/3	1402/4/6	Yes			IRR 38,000,000,000
5	5		2.1	Demolish Silo N(north)	58 days		1402/12/15	1402/12/15	Yes			IRR 19,000,000,000
6	6		2.1.1	Drilling for blasting operations	30 days	3	1402/12/29	1403/1/29	Yes	7	Drilling Team[4]	IRR 2,400,000,000
7	7		2.1.2	Placing flammable materials	7 days	6	1403/1/30	1403/2/5	Yes	8	Explosives Material[1]	IRR 10,000,000,000
8	8		2.1.3	Blasting operation	1 day	7	1403/2/6	1403/2/6	Yes	9	Explosives Team	IRR 800,000,000
9	9		2.1.4	Rebar Cuting	20 days	8	1403/2/7	1403/2/26	Yes	15	Air cutter[5],Angle Grinder[	IRR 5,800,000,000
10	10		2.2	Demolish Silo S(south)	58 days		1402/12/15	1402/12/15	Yes			IRR 19,000,000,000
11	11		2.2.1	Drilling for blasting operations	30 days	3	1402/12/29	1403/1/29	Yes	12	Drilling Team[4]	IRR 2,400,000,000
12	12		2.2.2	Placing flammable materials	7 days	11	1403/1/30	1403/2/5	Yes	13	Explosives Material[1]	IRR 10,000,000,000
13	13		2.2.3	Blasting operation	1 day	12	1403/2/6	1403/2/6	Yes	14	Explosives Team	IRR 800,000,000
14	14		2.2.4	Rebar Cuting	20 days	13	1403/2/7	1403/2/26	Yes	15	Air cutter[5],Angle Grinder[	IRR 5,800,000,000
15	15		3	Garbage collection	20 days	14,9	1403/2/27	1403/3/15	Yes	16	Loader,Simple worker[4],Sk	IRR 3,600,000,000
16	16		4	Finish	0 days	15	1403/3/15	1403/3/15	Yes			IRR 0

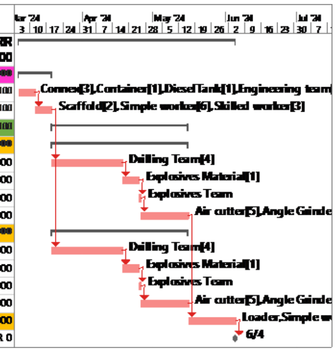
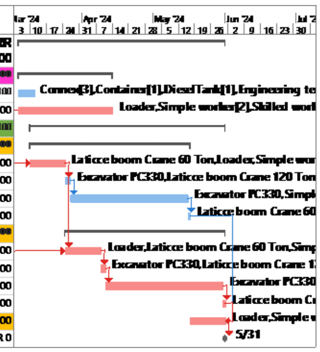


Table 8
MSP software output: Destruction of silo wall using excavator method

ID	ID	Task Mode	WBS	Task Name	Duration	Predecessors	تاریخ شروع	تاریخ پایان	Critical	Successors	Resource Names	Cost
0	0		0	Excavator Method Demolish for Section1	88 days		1402/12/14	1403/3/14	Yes			IRR 64,410,000,000
1	1		1	Site mobilization	40 days		1402/12/15	1403/3/14	Yes			IRR 29,970,000,000
2	2		1.1	Workshop Mobilization	7 days		1402/12/15	1402/12/21	No		Conrex[3],Container[1],Diesel	IRR 19,050,000,000
3	3		1.2	Purcumnet Soil	40 days		1402/12/15	1403/1/25	Yes	6SS+5 days	Loader,Simple worker[2],Sk	IRR 10,920,000,000
4	4		2	Demolish Silo	83 days		1403/2/3	1402/4/6	Yes			IRR 31,240,000,000
5	5		2.1	Demolish Silo N(north)	68 days		1402/12/15	1402/12/15	Yes			IRR 15,620,000,000
6	6		2.1.1	Filling Soil intire Silo	15 days	3SS+5 days	1402/12/20	1403/1/5	Yes	7,11	Laticce boom Crane 60 Ton	IRR 4,500,000,000
7	7		2.1.2	Transfer Excavator above Silo	2 days	6	1403/1/6	1403/1/7	No	8	Excavator PC330,Laticce bo	IRR 1,920,000,000
8	8		2.1.3	Demolish Wall by PC330	50 days	7	1403/1/8	1403/2/26	No	9	Excavator PC330,Simple wo	IRR 9,000,000,000
9	9		2.1.4	Transfer Excavator below Silo	1 day	8	1403/2/27	1403/2/27	No	15FF	Laticce boom Crane 60 Ton	IRR 200,000,000
10	10		2.2	Demolish Silo S(south)	68 days		1402/12/15	1402/12/15	Yes			IRR 15,620,000,000
11	11		2.2.1	Filling Soil intire Silo	15 days	3SS+5 days,6	1403/1/6	1403/1/20	Yes	12	Loader,Laticce boom Crane	IRR 4,500,000,000
12	12		2.2.2	Transfer Excavator above Silo	2 days	11	1403/1/21	1403/1/22	Yes	13	Excavator PC330,Laticce bo	IRR 1,920,000,000
13	13		2.2.3	Demolish Wall by PC330	50 days	12	1403/1/23	1403/3/10	Yes	14	Excavator PC330,Simple wo	IRR 9,000,000,000
14	14		2.2.4	Transfer Excavator below Silo	1 day	13	1403/3/11	1403/3/11	Yes	15FF	Laticce boom Crane 60 Ton	IRR 200,000,000
15	15		3	Garbage Soil Transfer	15 days	14FF,9FF	1403/2/28	1403/3/11	Yes	16	Loader,Simple worker[4],Sk	IRR 3,200,000,000
16	16		4	Finish	0 days	15	1403/3/11	1403/3/11	Yes			IRR 0



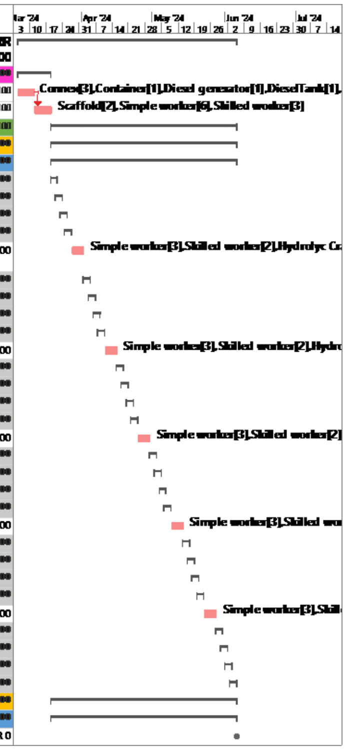
the WBS is first prepared for each demolition method, and then by defining the relationship between activities and allocating resources, the duration of activities is calculated, and the total demolition time is obtained using the above method.

The evaluation results of each demolition method based on the time and cost criteria are as follows, according to the predicted schedule output in MSP and the calculation of costs based on the resources allocated to the activities. Table 6 shows Results of time and cost of implementing each method.

Table 6 shows that in the wall area of the silo, the concrete cutting method is the cheapest, but from a safety perspective, the demolition method using an excavator has better safety. In this work area, the choice of demolition method will be made based on the AHP evaluation. In the ceiling, column, and foundation areas of the silos, the shortest time and lowest cost are achieved using the demolition method with an excavator. Also, according to the safety assessment, compared to the explosion method, the demolition method using an excavator has a higher safety factor. Given the absolute superiority of the demolition method using an excavator in terms of cost, time, and safety, the proposed demolition method for the ceiling, column, and foundation sections of the silos is demolition using an excavator. In the concrete cutting method, the gross execution cost is higher than the demolition method using an excavator, but this is due to the purchase of equipment and machinery required for this method. Assuming a 30% depreciation of the required equipment and machinery in this method within 3 months, the book value of the assets after deducting depreciation is less than the demolition method using an excavator. However, it should be noted that if concrete cutting is chosen, the project manager must consider the cost of purchasing the necessary machinery and equipment for this method, which requires a strong financial capacity for the project.

Table 9
MSP software output: Silo wall demolition using concrete wire cutting method

ID	ID	Task Mode	WBS	Task Name	Duration	Predecessors	تاریخ شروع	تاریخ پایان	Critical	Successors	Resource Names	Cost
0	0		0	**Wire Cut Method Demolish for Section1**	**93 days**		**1402/12/14**	**1403/3/14**	**Yes**			**IRR 87,880,000,000**
1	1		1	Site mobilization	14 days		1402/12/15	1403/3/14	Yes			IRR 67,088,000,000
2	2		1.1	Workshop Mobilization	7 days		1402/12/15	1402/12/21	Yes	3	Cornex[3],Container[1]	IRR 36,500,000,000
3	3		1.2	Scaffolding intire Silo	7 days	2	1402/12/22	1402/12/28	Yes	87,8	Scaffold[2],Simple worl	IRR 30,588,000,000
4	4		2	Demolish Silo	79 days		1403/2/3	1402/4/6	Yes			IRR 20,792,000,000
5	5		2.1	Demolish Silo N(north)	79 days		1403/2/3	1403/3/12	Yes			IRR 10,400,000,000
6	6		2.1.1	Wall of Silo N	79 days		1403/2/3	1403/2/15	Yes			IRR 10,400,000,000
7	7		2.1.1.1	Section 1 Level 15to 17m Silo	3 days		1403/2/3	1403/2/4	Yes			IRR 260,000,000
10	10		2.1.1.2	Section 2 Level 15to 17m Silo	3 days		1403/2/3	1403/2/4	Yes			IRR 260,000,000
13	13		2.1.1.3	Section 3 Level 15to 17m Silo	3 days		1403/2/4	1403/2/5	Yes			IRR 260,000,000
16	16		2.1.1.4	Section 4 Level 15to 17m Silo	3 days		1403/2/4	1403/2/5	Yes			IRR 260,000,000
19	19		2.1.1.5	Change Scaffold Level from 15 to 12m	5 days	18	1403/1/9	1403/1/13	Yes	21	Simple worker[3],Skilled	IRR 840,000,000
20	20		2.1.1.6	Section 1 Level 12 to 15 m Si	3 days		1403/2/5	1403/2/6	Yes			IRR 260,000,000
23	23		2.1.1.7	Section 2 Level 12 to 15 m Si	3 days		1403/2/5	1403/2/6	Yes			IRR 260,000,000
26	26		2.1.1.8	Section 3 Level 12 to 15m Sil	3 days		1403/2/6	1403/2/7	Yes			IRR 260,000,000
29	29		2.1.1.9	Section 4 Level 12 to 15 m Si	3 days		1403/2/6	1403/2/7	Yes			IRR 260,000,000
32	32		2.1.1.10	Change Scaffold Level from	5 days	31	1403/1/23	1403/1/27	Yes	34	Simple worker[3],Skil	IRR 840,000,000
33	33		2.1.1.11	Section 1 Level 9 to 12 m Silo	3 days		1403/2/7	1403/2/8	Yes			IRR 260,000,000
36	36		2.1.1.12	Section 2 Level 9 to 12 m Silo	3 days		1403/2/7	1403/2/8	Yes			IRR 260,000,000
39	39		2.1.1.13	Section 3 Level 9 to 12 m Silo	3 days		1403/2/8	1403/2/9	Yes			IRR 260,000,000
42	42		2.1.1.14	Section 4 Level 9 to 12 m Silo	3 days		1403/2/8	1403/2/9	Yes			IRR 260,000,000
45	45		2.1.1.15	Change Scaffold Level from	5 days	44	1403/2/6	1403/2/10	Yes	47	Simple worker[3],Skil	IRR 840,000,000
46	46		2.1.1.16	Section 1 Level 6 to 9 m Silo	3 days		1403/2/9	1403/2/10	Yes			IRR 260,000,000
49	49		2.1.1.17	Section 2 Level 6 to 9 m Silo	3 days		1403/2/9	1403/2/10	Yes			IRR 260,000,000
52	52		2.1.1.18	Section 3 Level 6 to 9 m Silo	3 days		1403/2/10	1403/2/11	Yes			IRR 260,000,000
55	55		2.1.1.19	Section 4 Level 6 to 9 m Silo	3 days		1403/2/10	1403/2/11	Yes			IRR 260,000,000
58	58		2.1.1.20	Change Scaffold Level from	5 days	57	1403/2/20	1403/2/24	Yes	60	Simple worker[3],Skil	IRR 840,000,000
59	59		2.1.1.21	Section 1 Level 3 to 6 m Silo	3 days		1403/2/11	1403/2/12	Yes			IRR 260,000,000
62	62		2.1.1.22	Section 2 Level 3 to 6 m Silo	3 days		1403/2/11	1403/2/12	Yes			IRR 260,000,000
65	65		2.1.1.23	Section 3 Level 3 to 6 m Silo	3 days		1403/2/12	1403/2/13	Yes			IRR 260,000,000
68	68		2.1.1.24	Section 4 Level 3 to 6 m Silo	3 days		1403/2/12	1403/2/13	Yes			IRR 260,000,000
71	71		2.1.1.25	Change Scaffold Level from	5 days	70	1403/3/3	1403/3/7	Yes	73	Simple worker[3],Skil	IRR 840,000,000
72	72		2.1.1.26	Section 1 Level 0 to 3 m Silo	3 days		1403/2/13	1403/2/14	Yes			IRR 260,000,000
75	75		2.1.1.27	Section 2 Level 0 to 3 m Silo	3 days		1403/2/13	1403/2/14	Yes			IRR 260,000,000
78	78		2.1.1.28	Section 3 Level 0 to 3 m Silo	3 days		1403/2/14	1403/2/15	Yes			IRR 260,000,000
81	81		2.1.1.29	Section 4 Level 0 to 3 m Silo	3 days		1403/2/14	1403/2/15	Yes			IRR 260,000,000
84	84		2.2	Demolish Silo S(south)	79 days		1403/2/3	1403/3/12	Yes			IRR 10,352,000,000
85	85		2.2.1	Wall of Silo S	79 days		1403/2/3	1403/2/15	Yes			IRR 10,352,000,000
163	163		3	Finish	0 days	162,83	1403/3/16	1403/3/16	Yes			IRR 0



Subsequently, the schedule and cost calculated based on the allocated resources in the MSP software are presented for each demolition method in Table 7,8 and 9.

Given the known cost and time values for each demolition method for the silo wall, pairwise comparison matrices are constructed in the AHP method for evaluating cost and time. Matrices 2 and 3 are the pairwise comparison matrices for evaluating cost and time in the AHP method, as calculated below.

Matrix 2 Pairwise comparison matrix values in the AHP method for cost evaluation:

$$\begin{pmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{pmatrix} = \begin{pmatrix} 1 & 0.91 & 0.76 \\ 1.1 & 1 & 0.83 \\ 1.31 & 1.2 & 1 \end{pmatrix}$$

$$C_{12} = \frac{1}{C_{21}}, C_{13} = \frac{1}{C_{31}}, C_{23} = \frac{1}{C_{32}}$$

Matrix 3 Pairwise comparison matrix values in the AHP method for time evaluation:

$$\begin{pmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{pmatrix} = \begin{pmatrix} 1 & 0.96 & 0.9 \\ 1.04 & 1 & 0.94 \\ 1.12 & 1.06 & 1 \end{pmatrix}$$

$$T_{12} = \frac{1}{T_{21}}, T_{13} = \frac{1}{T_{31}}, T_{23} = \frac{1}{T_{32}}$$

In the above matrices: C_{12} and T_{12} represent the score ratios (advantages) of the cost and time criteria, respectively, for the blasting method compared to the mechanical excavator method. Similarly, C_{13} and T_{13} denote the score ratios (advantages) of the cost and time criteria, respectively, for the blasting method compared to the concrete wire cutting method. Lastly, C_{23} and T_{23} represent the score ratios (advantages) of the cost and time criteria, respectively, for the mechanical excavator method compared to the concrete wire cutting method.

The diagonal elements of the matrix are equal to 1, as they represent the score ratios of the safety criterion of each method to itself. In these matrices, the higher the matrix element values, the lower the associated cost and time of that method.

6. Discussion and Results

With the obtained evaluation matrices for cost, time, and safety, in the final stage, a pairwise comparison matrix is constructed to make a decision regarding the importance (priority) of cost, time, and safety parameters in this project using the AHP method. The values of the pairwise comparison matrix for the cost, time, and safety parameters in this project are collected through a questionnaire and are based on the opinions of expert specialists in this field. It is worth noting that in each project, a pairwise comparison matrix exists for the decision criteria, and this matrix will be different for each project based on the importance indicators from the perspective of the client and contractor. For example, in this case study, considering the client's request for the earliest possible access to the iron ore reserve under the demolished silos, the importance of time is greater than cost, and due to the high sensitivity of the demolition operations and past accidents, the importance of safety is greater than all other criteria. Matrix 4 shows the values of the pairwise comparison matrix for the final decision criteria for each method in AHP.

Matrix 4 Pairwise comparison matrix values of decision-making criteria in the AHP method:

$$\begin{pmatrix} C(Cost) & C/T & C/S \\ T/C & T(Time) & T/S \\ S/C & S/T & S(Safety) \end{pmatrix} = \begin{pmatrix} 1 & 0.8 & 0.348 \\ 1.25 & 1 & 0.25 \\ 2.875 & 4 & 1 \end{pmatrix}$$

$$C/T = \frac{1}{T/C}, C/S = \frac{1}{S/C}, T/S = \frac{1}{S/T}$$

In the above matrix, the first to third rows correspond to the importance (priority) of the cost, time, and safety criteria, respectively. The inconsistency ratio of this matrix is 0.02, which is within the acceptable range (the inconsistency ratio in a pairwise comparison matrix should be less than 0.1). The result obtained from the hierarchical analysis using the AHP method for selecting the demolition method for silo walls (upper part) shows that the concrete cutting method, with a score of 0.362, is the best method considering cost, time, and safety criteria, followed very closely by the mechanical excavator method with a score of 0.360. The Figure 7 below shows the results of the hierarchical analysis using the AHP method in the Expert Choice software for selecting the demolition method for silo walls (upper part).

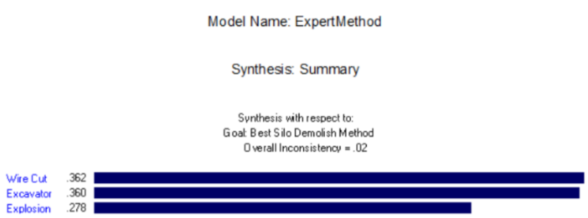


Figure 7 Results of AHP method analysis in Expert Choice software

7. Demolition Using the Selected Method

The wire saw method was chosen as the optimal approach for the upper sections of the silos and for the demolition of silo walls, based on the obtained results. The contractor and client approved this method for execution, and the demolition was carried out accordingly.

The initial concept of using a concrete wire saw and examining its construction management aspects in demolishing concrete structures was introduced by K. Walker and colleagues in 1996 [22], concerning the demolition of concrete chimneys in Arizona, USA. The study summarized and compared three methods: blasting, mechanical demolition, and wire saw cutting with diamond tools. According to their findings, the wire saw method saved approximately 7% in time compared to other methods. By designing the cutting and segmentation process effectively, the project was successfully completed. The study concluded that accurately estimating the structure's geometry and conducting an economic analysis of methods play crucial roles in selecting the optimal method.

Vasiliy Shalenny in 2019 [23] highlighted several key aspects of demolishing concrete structures using diamond wire saws. These include:

1. Installing the cutting device on a temporary support structure rather than directly on the primary structure.
2. Utilizing remote control to operate the cutting device.
3. Using scaffolding for positioning operational personnel and equipment.
4. Establishing reliable methods for lowering cut pieces to the ground.

Based on the results of these studies, the execution procedure, and the silo structural drawings, the walls of each silo were divided into segments, with each segment forming a quarter-circle. These segments were cut at various levels using a concrete wire saw and lowered to the ground using a crane. The weight and dimensions of the cut concrete segments are detailed in the lifting plan calculations provided in the following section.

Notable advantages of this method include precision in concrete cutting, reduced dust and pollution due to water usage, no limitations on the depth and dimensions of the concrete segment owing to the adjustable length of the diamond wire, and no noise or vibration pollution on-site [24]. Additionally, as Shedge concluded in 2024 [25], the wire saw method—also referred to as the "silent demolition method"—is well-suited for sensitive environments due to its reduced noise and vibration.

Sergio Baragetti and colleagues in 2023 [26] developed a numerical FEM model (finite element method) to optimize stress and deformation conditions in diamond wire used for concrete demolition. They found that micro-cracks and small grooves in the wire are primarily due to the misalignment of beads during wire assembly. This allows water penetration, causing corrosion of the metal core, shortening the wire's lifespan, and reducing its fatigue resistance. The study also demonstrated that stress concentration at the wire-to-bead connections is the most critical factor for poor performance. Areas where the wire is in direct contact with the beads are more susceptible to failure due to contact stresses and fatigue from corrosion. To mitigate these stresses, selecting precise parameters such as wire diameter, tensile load, the Young's modulus of the plastic coating, and pulley diameter can reduce Von Mises stresses, increase wire durability, and improve equipment performance.

The introduction of a safety monitoring system during wire saw demolition in concrete structures by Berend Denkena in 2022 [27] further enhances operational reliability. Using inductive sensors adaptable to harsh working conditions, this system identifies minor failures before significant issues arise, monitors wire movement, ensures the stability of the diamond wire, detects positional changes in diamond segments, and predicts tool failures.

Before operating the wire saw equipment, a scaffold platform was constructed inside the silos to facilitate operation at various levels. Two cutting devices were positioned inside each silo, working simultaneously to cut concrete segments. Once a segment was cut, it was lowered to the ground using a crane.

The scaffold design complied with the execution drawings, using Omega (triangular) scaffolding arranged to approximate the circular shape inside the silos and on their roofs. The base of the primary structure consisted of square frames measuring 1.2m x 1.2m with a height of 1m. Diagonal bracing was added to enhance resistance and performance. The spacing between the triangular elements (square bases) was 1m.

As only quarter-circle segments were cut where demolition was planned, the scaffolding was in close contact with the silo wall in those areas, while maintaining a distance of approximately 50cm from the inner wall edge in other regions.

Each cutting device weighed about 350–400kg and measured 1m x 1m. Two devices operated on each platform, each requiring two personnel, bringing the total applied load to approximately 1000kg (1 ton). According to the manufacturer's design, the formwork platform had a load capacity of 1 ton per square meter, ensuring sufficient resistance with a high safety factor.

The execution of the scaffold and the layout of planks to create a platform for positioning the concrete cutting equipment is illustrated in the accompanying diagram. The figure 8 and 9 shows many pictures from this method.

Figure 8. From the right, in order, scaffolding is implemented inside the silos to create a platform for the placement of concrete cutting machines, Chinese planks are placed on the scaffolding to place concrete cutting equipment, and concrete cutting equipment is placed.

During the demolition of silo walls using the wire saw method, the creation of three simultaneous work fronts significantly improved project performance by reducing time and labor costs. On this platform, three devices operate concurrently:

1. A horizontal cutting machine that uses a wire to cut concrete horizontally.
2. A vertical cutting machine that performs vertical concrete cutting.
3. A concrete coring machine used to drill boreholes for passing the wire saw and creating connection points for the crane hook.

One of the key requirements for establishing these simultaneous work fronts was ensuring the safety measures for these activities. To protect the operators of the concrete cutting machines, a safety guard and shield were installed on the platform using scaffolding and metal sheets. This measure ensures no harm or damage occurs to individuals in case the wire saw snaps. Additionally, a separate metal safety guard was installed to ensure the safety of the operator performing the coring activity. To enhance job safety and reduce risks, remote control is utilized for switching the wire saw machines on and off.

Figure 9. Simultaneous creation of three work fronts in the concrete wire cutting demolition method (simultaneous use of two horizontal and vertical cutting machines along with a concrete cutter)

In this method, the sequence of concrete cutting in horizontal and vertical directions is crucial. Initially, horizontal cuts must be executed first, followed by vertical cuts. Alternatively, if both horizontal and vertical cuts are to be performed simultaneously, it must be planned so that the horizontal cutting is completed first and then the vertical cutting. Otherwise, if the vertical cutting is finished before the horizontal cutting, the weight of the cut concrete will rest on the wire saw and its segments. This can cause the wire saw to break frequently due to the immense gravitational load applied to the segments and the wire.

However, if the horizontal cut is completed before the vertical cut, the weight of the concrete does not bear on the wire saw. In this case, because the concrete piece remains connected to the structure at its sides, no significant force is exerted on the wire saw cutting the bottom portion.

Another key consideration in wire saw cutting is accounting for the location of connections and the concentration of structural reinforcements. Cutting should ideally avoid areas where two concrete pieces are joined, especially those with high reinforcement density.

As shown in the figure 10 below, the cutting location has a high concentration of structural reinforcements, which causes frequent breaking of the wire saw and its segments. This, in turn, reduces the execution speed of the operation.

Figure 10. Tearing of cutting wire at the point of compression of structural reinforcements.

In the final stage, before the concrete segment is fully detached from the structure, it is secured to the crane using a 20-mm steel cable. This ensures that when the segment completely separates from the structure, it is already supported by the crane. The crane then transfers the segment to the ground, after which it is transported by a trailer to either a permanent storage site or to be utilized in other parts of the plant. The Figure 11 shows transferring cut concrete pieces to the ground by crane.

Figure 11. Transferring the cut concrete piece to the ground by crane

In this case study, some of the cut concrete segments were repurposed as Jersey barriers for the path of mining dump trucks. The calculations for the load capacity of the crane and the method of securing the segments are detailed in the lifting plan presented later.

8. Lifting Plan

The design and calculation of the lifting plan have been carried out based on the guidelines of the China Work Safety and Health Council (WSH [28]). According to the site plan designed for the project, there are no obstacles within a 500-meter radius of the silos for crane movement. The lifting plan calculations have been performed based on the height of the two silos, which is 25 meters, and their diameter, which is 15 meters.

The following figure 12 shows a view of the two silos. Two lifting plans have been prepared for their demolition. The first plan involves removing the sections on the sides of the silos, assuming that the crane will move to the nearest location for lifting each section.

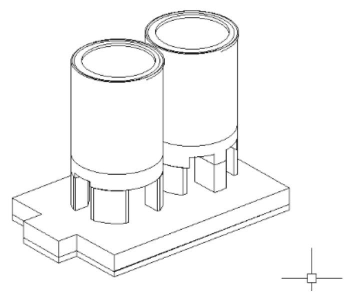


Figure 12. 3D view of existing silos

The second plan considers the scenario where the crane does not have the capability to move and position itself at the closest distance to the silo for lifting the sections.

Crane Specifications Determination: To determine the boom length, boom angle, and lifting radius, we utilize the charts and tables available in the crane’s operation manual [29]. Using this information, the maximum lifting capacity of the crane can be identified. For added safety, up to 75% of the crane's maximum capacity will be used. The figure 13 shows graph of changes in crane boom length and its corresponding angle.

The maximum length of the crane without jib and auxiliary jib is 50 meters. Since the load is not located in an area out of reach, there is no need to use the jib or auxiliary jib.

It is planned for the crane to carry loads between 20 and 25 tons, and to ensure project safety, only 75% of the maximum lifting capacity will be used. Based on the charts and dimensions of the silos, the boom length must be at least 31 meters.

Table 10.
Maximum permissible load based on boom length and crane distance from load center of gravity

Working radius (m)	13.6m Boom		20.4m Boom		27.2m Boom		34.0m Boom		40.9m Boom		45.5m Boom		50m Boom	
	360°	Over rear	360°	Over rear	360°	Over rear	360°	Over rear	360°	Over rear	360°	Over rear	360°	Over rear
3.35	120.00	←	50.00	←	40.00	←								
4.0	100.00	←	50.00	←	40.00	←								
4.5	87.20	←	50.00	←	40.00	←	32.00	←						
5.5	72.30	←	50.00	←	40.00	←	32.00	←	26.00	←				
6.5	59.00	←	50.00	←	40.00	←	32.00	←	26.00	←	20.00	←		
7.5	49.40	←	44.05	←	40.00	←	32.00	←	26.00	←	20.00	←	15.00	←
8.5	42.50	←	39.15	←	35.60	←	32.00	←	26.00	←	20.00	←	15.00	←
9.5	37.50	←	35.80	←	32.05	←	28.75	←	26.00	←	20.00	←	15.00	←
10.0	35.30	←	34.25	←	30.50	←	27.35	←	24.55	←	20.00	←	15.00	←
10.5	32.85	←	32.85	←	29.05	←	26.05	←	23.25	←	20.00	←	15.00	←
11.0	31.30	←	31.30	←	27.75	←	24.95	←	22.00	←	19.25	←	15.00	←
12.0	26.60	27.10	26.60	27.10	25.40	←	22.95	←	19.90	←	17.60	←	15.00	←
13.0			22.70	23.45	22.70	23.45	21.15	←	18.30	←	16.30	←	13.80	←
14.0			19.50	20.40	19.50	20.40	19.50	←	17.00	←	15.10	←	12.80	←
15.0			17.05	17.95	17.05	17.95	17.05	17.95	15.80	←	14.10	←	11.95	←
16.0			14.90	15.80	14.90	15.80	14.90	15.80	14.75	←	13.27	←	11.15	←
18.0			11.55	12.45	11.55	12.45	11.55	12.45	11.55	12.45	11.75	←	9.90	←
20.0					9.05	9.90	9.05	9.90	9.05	9.90	9.85	10.50	8.80	←
22.0					7.10	7.90	7.10	7.90	7.10	7.90	7.90	8.65	7.90	←
24.0					5.55	6.30	5.55	6.30	5.55	6.30	6.30	7.05	7.05	7.20
26.0							4.25	5.00	4.25	5.00	5.00	5.70	5.70	6.40
28.0							3.20	3.90	3.20	3.90	3.95	4.60	4.60	5.25
30.0							2.30	2.95	2.30	2.95	3.00	3.65	3.70	4.30
32.0							1.50	2.15	1.50	2.15	2.20	2.85	2.90	3.50
34.0									0.85	1.45	1.55	2.15	2.20	2.75
36.0											1.00	1.55	1.60	2.15
38.0													1.05	1.60
40.0													0.60	1.10
Standard hook	for 120 tons		for 50 tons										for 15 tons	
Hook weight	1,050kg		600kg										330kg	
Parts of line	14		6		5		4		3		3		2	
Min. boom angle									15°		30°		35°	

For optimal use of the crane, a boom length of 34 meters will be employed, as shorter boom lengths result in higher lifting capacities.

The maximum length of the crane without jib and auxiliary jib is 50 meters. Since the load is not located in an area out of reach, there is no need to use the jib or auxiliary jib.

It is planned for the crane to carry loads between 20 and 25 tons, and to ensure project safety, only 75% of the maximum lifting capacity will be used. Based on the charts and dimensions of the silos, the boom length must be at least 31 meters. For optimal use of the crane, a boom length of 34 meters will be employed, as shorter boom lengths result in higher lifting capacities.

The closer the boom angle is to a vertical position, the greater the lifting capacity. Similarly, a shorter lifting radius increases lifting capacity. Based on this, a lifting radius of 7.1 meters, a boom length of 34 meters, and an angle of 78 degrees are selected. In this configuration, the maximum load that the crane can lift is 32 tons, with 75% of this being 24 tons.

For the second plan, it is assumed that the crane will lift the load from the center of the silo. Accordingly, the boom length is adjusted to 45.5 meters, and the boom angle is set to 70 degrees. The lifting radius will also increase to 15 meters. Based on the provided charts, the maximum load in this configuration is 14.1 tons. For additional safety, only about 75–80% of this weight will be lifted, which amounts to 10.575 to 11.28 tons. The table 10 shows maximum permissible load based on boom length and crane distance from load center of gravity.

The figure 15 presents a view of a crane, demonstrating its position relative to the silo. The boom is positioned 2.2 meters away from the silo. Additionally, the distance between the tip of the crane and the building is considered to be 2.1 meters.

The Table 13 shows condition of lifting plan B in this project.

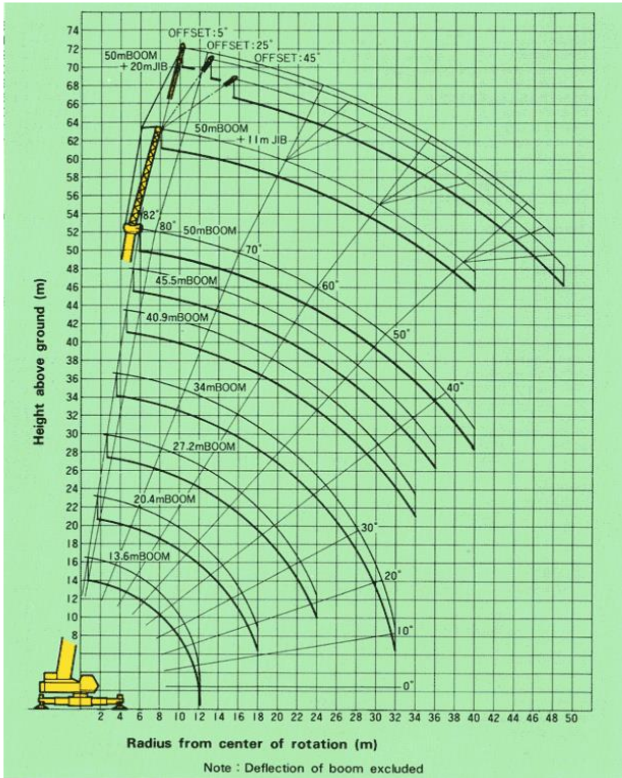


Figure 13. Graph of changes in crane boom length and its corresponding angle

Table 11

Crane Specifications

Boom Length	13.6m-50m
Jib length	11m-20m
Boom derricking Angle	-2-82
Boom derricking time	76sec
Boom Telescoping Speed	0.16m/sec

Table 12

conditions of lifting plan A

Lifting plan A	
crane info	NK-1200(120TON)
Lifting configuration	Main boom
Boom length	34m
Working radius	7.1m
swl	22ton
Height with jib	70m
Load Details	
description	Reinforced concrete parts
Dimension	3mx0.5mx5.8m
Center Of Gravity	Given □ Calculated □ Unknown ■
Calculation Loads	
Reinforced concrete parts weight	22ton
Extra weight(Hook, Gear,…)	2ton
Total Weight	24ton
Safety Factor	1.33
Crane Capacity Usage	75%
Routine Lift ■	Non Routine Lift □

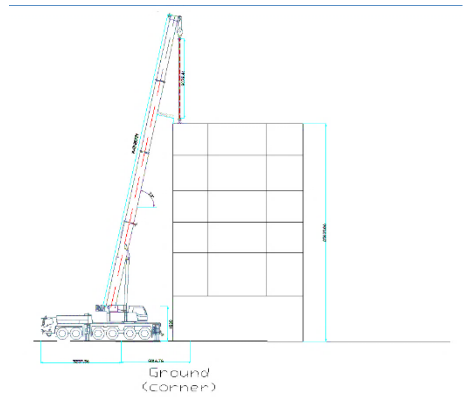


Figure 14. View of the crane in the lifting position of Plan No. 1 to pick up the concrete piece closest to the silo.

The figure 15 shows a crane. The crane's position in relation to the silo is depicted, with the boom one meter away from the silo. Additionally, the distance from the tip of the crane to the building is considered to be 3.8 meters.

The total loads of 24 tons and 10.5 tons represent the combined maximum load the crane can lift in the two presented scenarios. This load includes the weight of the hook and other accessories, which has been conservatively estimated at 2 tons. According to the provided chart, the actual weight of the crane hook is 0.6 tons.

Load Securing: The method of securing loads is critical as it affects the pressure exerted on the slings. The smaller the angle of the slings, the greater the pressure. For example, in some cases, a maximum angle limit of 45 degrees is enforced. Therefore, determining the proper angle during load lifting is essential to control the pressure on the slings.

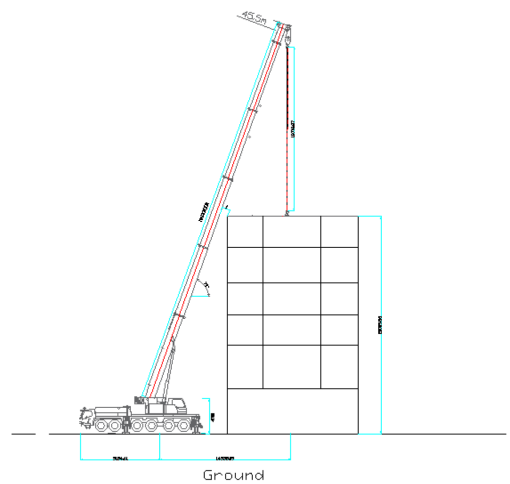


Figure 15. View of the crane in the lifting position of Plan No. 2 to lift the concrete piece at the farthest distance from the silo

Table 13
Condition of lifting plan B

Lifting plan B	
crane info	NK-1200(120TON)
Lifting configuration	Main boom
Boom length	45.5m
Working radius	15m
swl	10.5ton
Load Details	
description	Reinforced concrete parts
Dimension	3mx0.5mx2.26m
Center Of Gravity	Given □ Calculated □ Unknown ■
Calculation Loads	
Reinforced concrete parts weight	8.5ton
Extra weight(Hook, Gear,…)	2ton
Total Weight	10.5ton
Safety Factor	1.33
Crane Capacity Usage	75%
Routine Lift ■	Non Routine Lift □

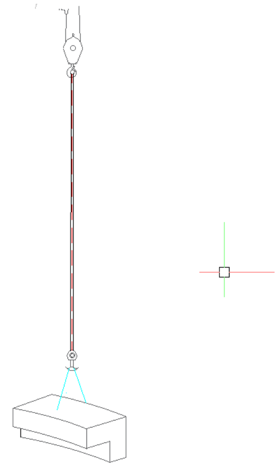


Figure 16. How to fasten and restrain a concrete piece with a crane hook

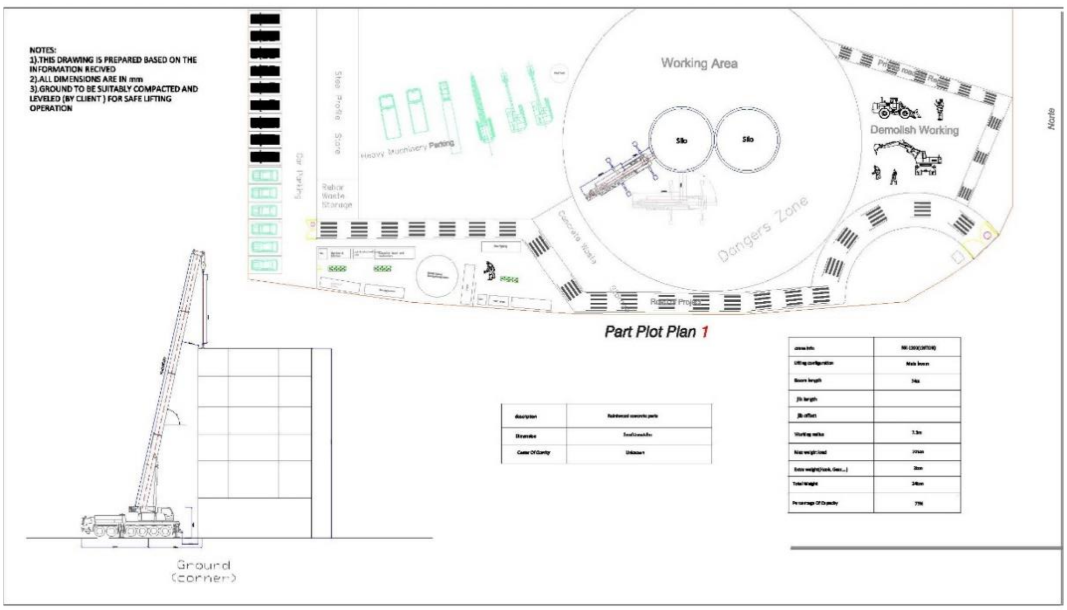


Figure 17. Project lifting plan with 120-ton crane

9. Project Workshop Site Plan Design

The design and calculation method for the workshop site plan of this project were prepared based on the research of Mr. Emad Elbeltagi [30]. A site layout includes the placement of buildings, parking areas, storage zones, access roads, and temporary facilities. An optimal site layout ensures maximum utilization of available space, reduces project costs, minimizes material movement during construction, improves accessibility, enhances site security, and promotes workplace safety.

Every project has a unique site layout plan tailored to its specific variables. The most important and primary variable in site layout planning, which drives decisions regarding site logistics, is the size and actual location of the site. A list of the key variables influencing site layout is provided in the illustration.

Elements of Site Layout Planning: A well-planned site that includes all temporary facilities and auxiliary elements results in:

1. Increased productivity and safety.
2. Reduced space required for temporary construction.
3. Maximum utilization of resources.

Table 14
Effective tips for designing a project workshop plan website

No.	Description	Details
1	Fire Prevention	Fire is one of the main causes of damage at construction sites. Therefore, the presence of fire extinguishers is a necessity for any construction project.
2	Medical Services	A first aid kit is essential in construction projects. For remote projects, a well-equipped medical room with a doctor and nurse is important.
3	Safety Gear	Workers must use safety equipment such as safety shoes, helmets, gloves, and protective glasses.
4	Site Access	Easy access to the site improves equipment drivers' morale, reduces the likelihood of accidents, and saves transport time. For large projects, proper planning for road designs leading from nearby highways is necessary. Internal roads are also vital for smooth operations. Parking facilities for the owner, administrative and technical staff, and construction personnel must be planned in available spaces.
5	Site Map	It should outline project details and be displayed at the site manager's or project manager's office as well as at the entrance gate.
6	Traffic Guidance Signs	In large projects, these signs direct site traffic and prevent accidents.
	Display of Safety Rules and Workforce Policies	This can help eliminate disputes between labor and management.
	Emergency Routes and Underground Services	Emergency escape routes should be displayed on every floor as construction progresses. The locations of underground services must be identified to avoid damage.
7	Entrance	Adequate security at the site entrance is essential. All visitors' entries and exits must be recorded.
8	Lighting	A backup generator is necessary to provide site lighting.
9	Fencing	Site boundary fencing is important for security purposes.
10	Accommodation	In large construction projects, providing accommodation facilities for various project personnel is essential.
11	Offices	Offices should be located close to each other, adjacent to the site, and in a secure area. They should also be equipped with appropriate office supplies. The site offices typically include work offices, the general contractor's office, and the subcontractors' and consultants' offices.
12	Water and Sanitation	Providing water and sanitation facilities in appropriate locations for staff is essential.
13	Material Handling	Over one-third of construction operations involve material handling. Using appropriate equipment and advanced planning to reduce material handling can directly lower costs and save time.
14	Storage and Site Cleaning	Planning and reserving areas for storing materials is necessary to avoid multiple relocations.
15	Storage Locations	These are used for temporary or long-term storage of materials and equipment.
16	Covered Warehouses	Materials are stored here until use.
17	Stockpile Areas	These areas are used for short-term material storage close to the work area.
18	Site Cleaning	Cleaning is essential at the workplace, especially in areas generating significant waste. Regular waste disposal must be ensured.
19	Workers' Changing Rooms	These rooms provide appropriate spaces for changing clothes, washing, and resting during waiting periods.
20	Temporary Facilities	Recognizing the characteristics of temporary facilities before site layout planning is important. Key features include: - Compliance with safety and environmental regulations. - Reusability. - Ease of assembly and disassembly.

The table 14 presents the key considerations for proper site layout planning and the design of the workshop site plan.

Table 15
Requirements for equipping a construction project workshop

Facility No.	Facility Name	
1	Job office	*
2	Owner representatives office	*
3	Subcontractors office	*
4	First aid office	
5	Information and guard house	
6	Toilet on site	*
7	Staft/Engineer dormitory	*
8	Statt/Engineer family dormitory	
9	Labor dormitory	
10	Labor family dormitory	
11	Dinning room for labor	
12	Bathroom for labor	
13	Restroom for labor	
14	Equipment maintenance shop	
15	Parking lot for mechanics	*
16	Prefabricated rebar storage yard	*
17	Rebar fabrication yard	
18	Fabricated rebar storage yard	
19	Carpentry shop	
20	Storage yard for lumber	*
21	Storage yard for formed lumber	
22	Cement warehouse	
23	Batch-plant and aggregate storage	
24	Craft change-house	*
25	Sampling / Testing lab	
26	Pipe jointing yard	
27	Pipe storage yard|	
28	Welding shop	*
29	Parking lot	*
30	Tank	*
31	Long tenn laydown storage	
32	Machine room	*
33	Electrical shop	
34	Steel fabrication shop	*
35	Sandblast shop	
36	Painting shop	
37	Scaffold storage yard	*
38	Material warehouse	*

Table 16
Estimating the space required for temporary project facilities

Temporary Facility	Minimum (m2)	Average (m2)	Maximum (m2)
Craft change house per worker	0.09	1.02	2.7
Time office per office worker	5.4	8.7	13.5
Number of people per brass alley (with average area per person)	100 Person	175 Person	250 Person
Number of workers per parking space	1	0.37	4
Area required for each unit parking	22.5	30	36

Once the required temporary facilities have been selected for the site, their necessary sizes must be estimated. The sizing of temporary facilities is primarily determined by labor force requirements, estimated work volume, production rates, site space availability, and cost considerations. Some safety regulations and other criteria for determining the size of temporary facilities are explained in the Table 16, 17 and 18.

Table 17
Space required for temporary offices in the project workshop equipment

Office	Size Range (m²)
Project Manager	12 - 25
Construction Manager	9 - 14
Mechanical, Electrical, Civil Engineer per	9 - 11
Purchasing (total)	46 - 84
Schedule & Cost Control (total)	28 - 93
Accounting (total)	37 - 80
First Aid & Safety per Office	17 - 19
Clerical (total)	28 - 74
Estimator	11

Based on the tables above and the equation 3, the required space for the project's site facilities is calculated:

$$A_n = (Q_{max}/I_m)/q_n \quad (4)$$

Where: $Q_{max} = q_{daily} \times t \times k_{qdaily} = Q_{total}/T$

Q_{max}: Maximum estimated quantity in storage space;

I_m: Utilization index for materials;

q_n: quantity of materials can be stored per m²;

Q_{total}: Total quantity of materials required for the project;

q_{daily}: estimated quantity required per day;

T: construction period (not total project duration);

t: Average stock (days); and

k: Fluctuation factor

10. Conclusion

In today's world, with the aging of old structures and the development of modern construction technologies, demolition projects for obsolete structures have witnessed significant growth. While construction methods are popular topics in modern construction management, this paper delved into demolition methods in detail. At first glance, it may seem that blasting is the most common and suitable method for demolishing concrete structures. However, as demonstrated in this paper, other demolition methods, such as using diamond wire cutting and demolition with excavators, are simpler, cost-effective, and time-saving alternatives. Moreover, they offer higher safety levels.

Project Manager: 1 person → 1 room 18 m^2

Site Manager: 1 Person → 1 room 18 m^2

Construction Manager: 2 Persons → 1 room 18 m^2

technical office (Civil & Mechanical ENG): 4 persons → 1 room 36 m^2

Schedule & Cost Control: 1 person
Accounting: 1 person
Officer: 1 Person
} 1 room 18 m^2

Worker: 20 Persons → 2 room for rest & Lunch 2*18 m^2

Concrete Demolish Team: 10 Persons → 1 room for rest & Lunch 18 m^2

Wire rope team: 5 Persons
Drilling team: 5 Person
} 1 room for rest & Lunch 18 m^2

HSE Manager: 1 Person
HSE ENG: 1 person
} 1 room 18 m^2

Total Manpower: 53 Persons → Safety & Area Per Office 10*15 m^2 = 150 m^2

According Table 2:

Time office per worker → 53*13.5 m^2 = 715 m^2

Area Required for each unit car parking → 6*36 m^2 = 216 m^2

Area Required for each unit Pickup parking → 3*40 m^2 = 120 m^2

Area Required for each unit Excavator parking → 2*(30*10) m^2 = 600 m^2

Area Required for each unit Crane parking → 2*(30*10) m^2 = 600 m^2

Area Required for each unit Loder parking → 1*(20*10) m^2 = 200 m^2

Area Required for each unit Truck parking → 2*(15*7) m^2 = 210 m^2

Area Required for each unit Trolley parking → 1*(30*10) m^2 = 300 m^2

Based on the calculations, the site layout and workshop plan for this project shows in Figure 18.

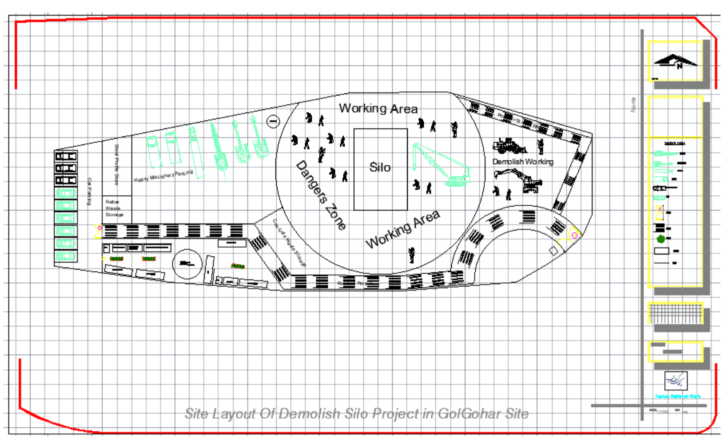


Figure 18 Site design map, project workshop plan

This study used a case study in Iran to analyze the demolition of a concrete silo by comparing various methods from cost, time, and safety perspectives using the Analytic Hierarchy Process (AHP). Time assessment was carried out using MSP software, while the costs for each method were estimated based on resources allocated to each operational phase in the Work Breakdown Structure (WBS). Safety evaluation combined AHP and DEA methods, gathering required data through questionnaires completed by domain experts. Results indicated that diamond wire cutting achieved the highest score among demolition methods. Additionally, according to silo modeling in SAP2000 software, single-stage silo overturning by removing primary columns was determined to be unfeasible.

A construction manager must have comprehensive oversight of all aspects of a construction project. As crucial as management and supervision during execution are, the feasibility study and selection of operational methods hold equal significance before construction begins. This paper aimed to cover essential aspects of demolition management from the initial phase (Phase Zero) through the project's final stages. It also presented a step-by-step approach to managing a demolition project through a case study.

Initially, all potential demolition methods were listed, considering the project’s constraints. This list was compiled using previous research and the experiences of construction managers. Each method was then scored and compared based on core criteria, including cost, time, and safety. Finally, the most suitable demolition method was selected.

A key advantage of the outlined methods is their adaptability to project-specific priorities; in AHP, users can create pairwise comparison matrices based on the relative importance of evaluation criteria. The case study demonstrated that the optimal method was diamond wire cutting. This paper comprehensively reviewed all concrete demolition methods, compared them, and provided a detailed explanation of each.

After selecting the demolition method, a lifting plan was created to optimize its execution. This highlights the need for construction managers to understand operational workflows fully before project commencement to direct progress effectively, avoiding unforeseen circumstances. The final stage involved designing the project’s site plan to maintain order and organization, an essential factor for an efficient workspace. The actual project outcomes, based on the chosen method, were then presented.

Key findings indicate that preliminary evaluations and selecting an appropriate demolition method significantly contribute to project success. In this case study, execution costs totaled 45,000,000,000 IRR compared to the initial estimated cost of 47,280,000,000 IRR, underscoring the impact of an effective site plan in cost reduction. Additionally, while the anticipated execution duration was 73 days, the project was completed in 63 days due to concurrent work fronts and efficient resource management.

Beyond reducing time and costs, this project achieved a remarkable safety record, with no casualties or financial losses due to accidents. Although the highest safety risk associated with diamond wire cutting involved lowering concrete pieces, precise calculations and lifting plans ensured the project's safety. At the time of writing, only the upper sections of the silos were demolished, with the demolition of remaining silo parts planned for subsequent stages.

Lastly, simplicity is a pivotal factor in the success of construction projects. The primary objective of construction managers is project success, and simplifying complex issues in construction methods can undoubtedly increase success rates. This paper was written with the aim of teaching complex issues in a simple manner. Its authors firmly believe that practical applications of the content discussed can significantly aid managers in demolition projects, ensuring success.

For enthusiasts in this field, further exploration of combining Building Information Modeling (BIM) and its impact on demolition method efficiency is recommended. Future research could compare BIM results with this paper’s findings to derive more accurate conclusions and propose effective solutions for demolition method management.

Acknowledgements

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