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# 3D modelling of an Asbad (Persian windmill): a link between vernacular architecture and mechanical system with a focus on Nehbandan windmill

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## Abstract

Asbads (Persian windmills) present a multifaceted view of using heritage science. These mills are no longer in use due to advances in technology and the advent of new grinding systems. Windmills show perfect harmony between vernacular architecture and mechanical system. This paper aims to review and analyze the mechanism of one of these windmills in Iran and illustrate how these historical buildings can bridge the gaps between these two science branches for better understanding of cultural heritage. To that purpose, a precise 3D modelling of mechanical components and architectural elements is provided based on architectural survey, photographs and sketches. This study addresses how vernacular architecture, with the specific flexibility, can be considered as one of the most useful tools for human beings. Thus, one of the Iranian windmills in Nehbandan was selected through field studies to be modelled. In this construction, local materials such as wood, adobe and stone are used. Findings reveal that windmills and their architectural flexibility are consistent with mechanical components and address environmental needs.

**Keywords:** Asbad (Persian windmill), 3D modelling, Mechanical system, Vernacular architecture, Nehbandan windmill, Heritage science

## Introduction

Human beings have immemorially benefited from wind energy for different purposes, like moving sailing boats, cooling houses through circulation of outside air and operating machinery in agriculture [1]. For centuries, residents in certain areas of the world, where there are strong winds and water shortages, have been encouraged to find alternative sources of energy. They developed windmills, which constituted another technical innovation, by using vernacular building techniques and relying on the science of mechanics [2]. Moreover, there has been a new interest in reviving these systems due to

their simple design and low cost, as well as a high rate of energy generation at low wind velocities [3]. Windmills in Iran were designed to convert wind energy into mechanical energy through moving a wind wheel, which in turn activated a system of vertical rotation (axis) through a system of gears that in turn rotating the millstones to grind cereals and raise water from wells. The first windmills are thought to have been used for irrigation and milling in Sistan (Persia). They are believed to have an important function and gained rapid popularity throughout Europe and the Arab countries as illustrated in Table 1.

Nehbandan Windmills show how the residents responded to the environmental opportunities and constraints and mastered a traditional technology. This study is based on a characteristic environmental feature—the wind—as the driving force of windmills associated with

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**Table 1** History of windmills from 200 BC to the present

| Time                 | Location          | Description and results   |
|----------------------|-------------------|---|
| 200BC                | Persia (IRAN)     | Generally, windmills were used in Sistan region of modern Iran. They were used to grind grains [4–14]   |
| Seventh century      | Middle East       | In the Middle East, windmills were used to supply food. Then, merchants and the Crusaders transferred the idea to Europe [10, 15]   |
| Eighth century       | Europe            | The general principles of constructing Asian vertical axis windmills were established in Europe in the eighth century A.D. [5, 7]   |
| Twelfth century      | Northern Europe   | Windmills were used for drainage of river deltas, land reclamation and manufacturing. Wind power formed the core of rural economy until the beginning of the industrial revolution [10, 11, 16–21]  |
| Nineteenth century   | The United States | Windmills were constructed in the United States during the nineteenth century. They were used to pump water into farmlands and later to generate electricity for homes and industries. The industrial growth resulted in the decline of windmills [4, 9, 11, 12, 14, 16–19, 22] |
| Twentieth century    | –                 | The traditional wind power application expanded to encompass electricity production after the 1973 and 1979 oil crisis [4, 13, 14, 18, 19, 22–24]   |
| Twenty-first century | –                 | By the end of the twenty-first century, new energy infrastructures will definitely undergo significant changes. The future changes, which would include renewable energy resources, could help man achieve prosperity and health [8, 13, 25, 26]                                |

local materials like adobe and subsequently a developing technology. Studying windmills can shed more light on how harnessing natural energy and using local materials in architectural heritage helped residents create environmentally friendly structures in the past. In this paper, different mechanical components of windmill, their architectural features, and the relationship between these two parts will be discussed. The paper also sought to answer the following questions by studying Nehbandan windmills:

1. How can mechanical components affect the architectural features?

2. How can architectural design determine the complexity of a mechanical system?

The literature review demonstrates that earlier studies mainly focused on several categories. Some researchers have discussed the historical and technological aspects of the windmills in Iran. These studies show the old history of harnessing wind energy for various purposes [14, 27–35]. Sketching numerous windmills to provide information about this ancient structure and significant changes over centuries, other researchers have emphasized the historical aspects of windmills in East Asia and Europe [7–9, 15, 18, 19, 22, 36]. Some studies have focused on energy efficiency issues. These studies have mainly focused on obtaining the maximum amount of energy and the minimum structural changes in early windmills [4, 11, 23–25, 37–40]. Also, some studies have been carried out, showing digital and graphical representation of windmills in terms of the technology used and the functions intended. These studies aimed at determining the technical parameters of these windmills. For example, they show different types of windmills depending on the shape of their blades to grind cereals or

collect water from wells [2, 3, 41]. Finally; travel writers have described the operation of windmills. During their travels across eastern provinces of Iran, they sketched windmills or took pictures of them to illustrate their description of windmills [42–45]. This study has identified the precise details of the architectural elements and mechanical components of one of the windmills in Iran and the correlation of these two branches of science with 3D-modelling representation. This could be a way for future research to use novel technologies such as virtual reality or augmented reality to help better understanding of architectural heritage.

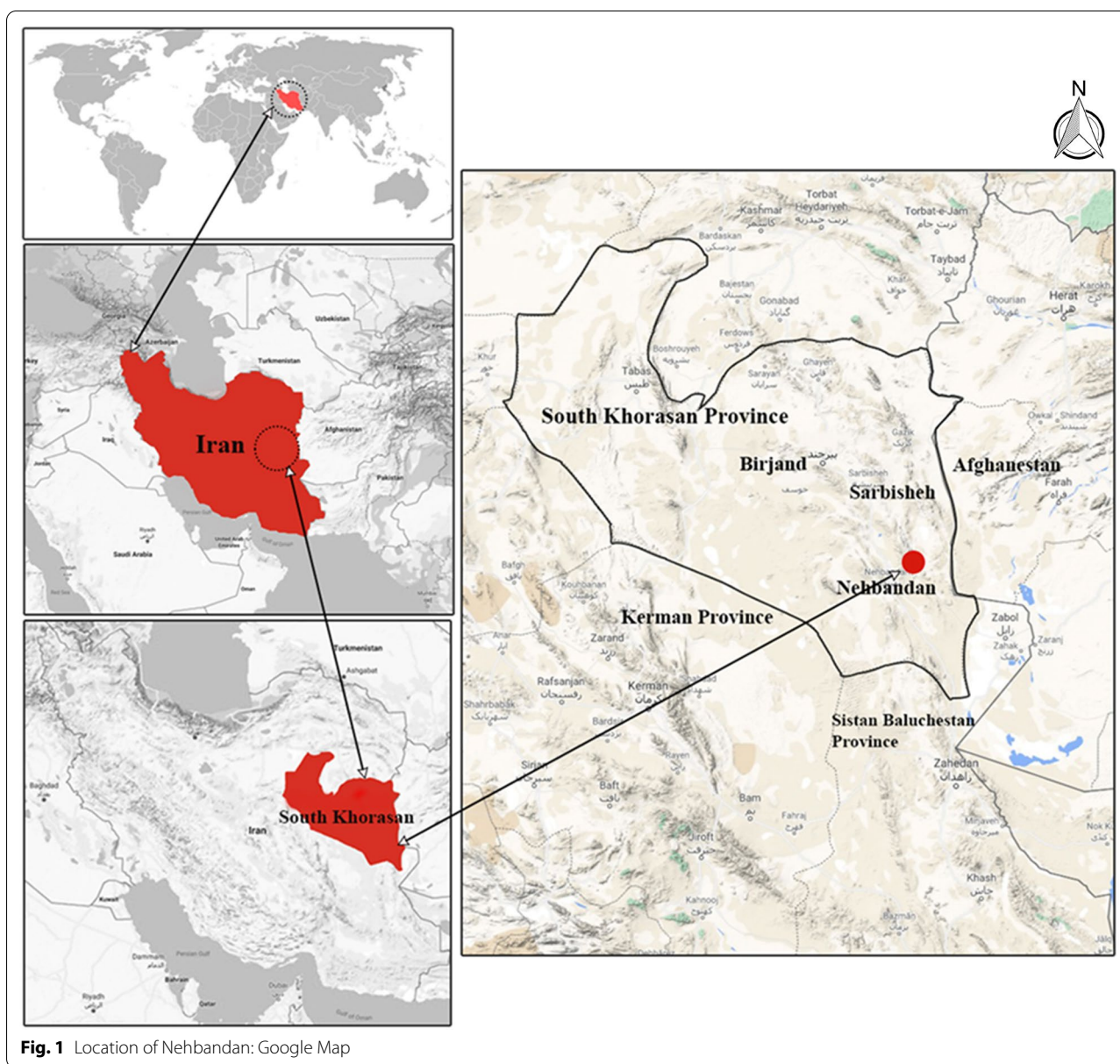
### Study area

Nehbandan is the largest city located in the southern part of South Khorasan Province in eastern Iran (Fig. 1). It is located between 31 degrees and 32 min of north latitude and 60 degrees and 2 min of east longitude [26]. Nehbandan borders on Afghanistan in the east, Sarbisheh City in the north, Birjand City in the west, Kerman Province in the southwest and Sistan and Baluchestan Province in the southeast.

The prevailing wind in this area is called 120-day wind that blows for 120 days from the heights of northeastern Iran to the southeastern lands. In Nehbandan, this wind lasts for 111 days from May 17th to September 5th [46]. The direction of the prevailing wind is north-northeast.

### Windmills in Nehbandan

Nehbandan windmills have a north-northeast orientation with regard to the direction of the prevailing wind (120-day wind) in this region [15]. These windmills have a major drawback: as they have vertical axis, they are only



responsive to prevailing wind direction and if the wind direction is different, they cannot be adjusted to it [38].

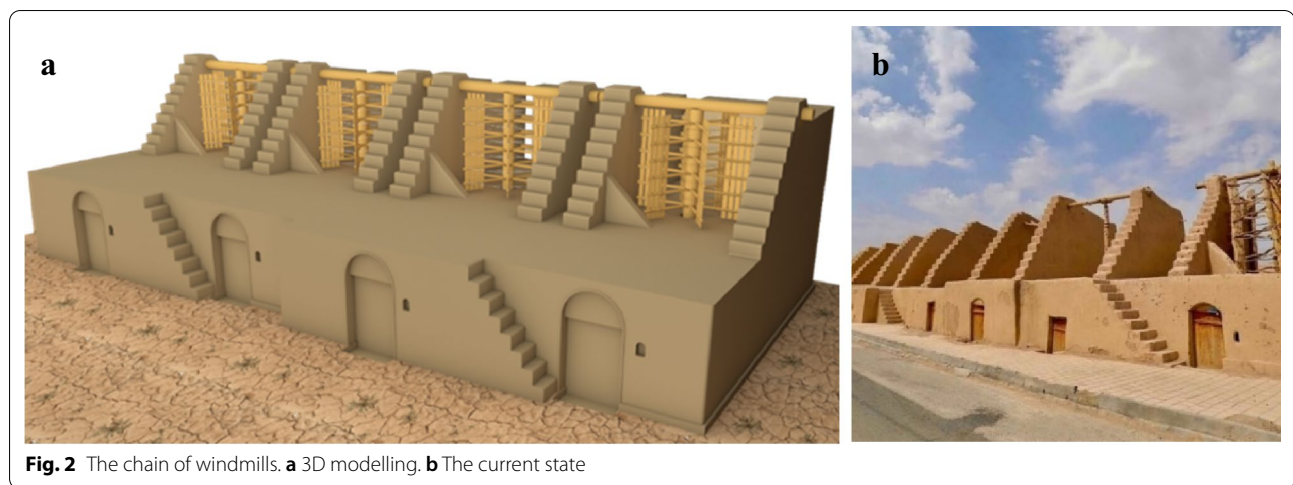
These windmills were not usually built as free-standing constructions; in other words, every four to five mills were attached to one another with the same architectural features and mechanical components and formed a chain of connected units [43] as shown in Fig. 2. Adjacency of the windmills also could neutralize probable propulsive forces and resisted strong winds such as the 120-day wind.

Iranian architecture is based on the use of eco-friendly and local materials. The Nehbandan windmill is not an exception and the local materials in the Khorasan

province such as stone, adobe and wood have been used to build these windmills [47].

Nehbandan windmill is a monument of historical and cultural interest. The historical importance of this windmill lies in the fact that it is one of the first windmills in the world. Nehbandan was part of Sistan province in the past, so as Table 1 shows, the history of these windmills goes back to 200BC although the exact year is not clear. In the past, there were 30 windmills in Nehbandan most of which have been destroyed or abandoned. The name of Nehbandan windmill comes from the region it is built in. Field observations show that some restorations implemented have been limited to applying a layer of straw on





the roof and surrounding walls in 2004. There is no conservation plan for these windmills nowadays.

On the other hand, the cultural importance of these windmills is that these historical buildings have been part of ordinary people's lives. The economic situation of residents relied on the operation of these windmills. People used these structures over hundreds of years as efficient machinery to meet their basic needs such as grinding wheat.

## Methods

This study is based on documentary and field research. The findings are the results of the authors' years of research on various windmills in Iran. Since many of these windmills have been destroyed due to climate change, the most challenging part of the study was accessing precise mechanical and architectural details.

To that aim, one windmill in Nehbandan, which is still standing and can be distinguished in terms of architectural features and mechanical elements, was chosen. This windmill has undergone minimal changes in the mechanical components. A vast amount of fieldwork, including photographs, sketches, architectural surveys and interviews with former millers were conducted to collect reliable information on the operation of the windmill and to acquire 3D data. Caliper, Micrometer and Feeler gauge were used to document the various mechanical components of the windmill. In addition, tape measure, digital level, compass, plummet and camera were used for architectural survey. Then a model based on computer-aided design (CAD) techniques was developed. Also, data obtained from previous research contributed to developing an accurate understanding of the ways these windmills operated.

## 3D modelling

First, a schematic representation of the objects, elements and properties of the windmill was produced to develop a three-dimensional model. Modelling was carried out before and after visits to the windmill. Due to the absence of plans for the windmill under investigation, or any reliable historical information in previous research, the field work was undertaken rigorously using empirical techniques for direct measurement and architectural surveys, through which the dimensions of all of the elements were determined. Following the first visits, the model was updated using new information obtained from subsequent visits. Thus, the 3D modelling was performed using Google SketchUp 2015 to create models of both the machinery and the mill.

## Results and discussion

Each windmill is a two-story building. The lower story is named Askhaneh, and the upper story is named Parkhaneh, as depicted in Fig. 3. The three-dimensional modelling of the windmill reveals how mechanical components affect the architectural design and how architectural design determines the complexity of the mechanical system. Thus, architectural features and the mechanical components of each story will be discussed in this study.

### A: Parkhaneh

In this section each mechanical components and architectural features of Parkhaneh will be discussed:

#### Mechanical components

- The Kharpol is a horizontal cylindrical wooden beam with a 6 m length and 0.14 m diameter (Fig. 4 Detail A; Fig. 5). It rests on the surrounding walls on both sides. Kharpol prevents any lateral movements of Tirpol. It is made of pine wood.



**Fig. 3** Parkhane and Askhaneh in a windmill. **a** 3D modelling. **b** The current state

- The Tirpol is the central vertical axis of the windmill with a 5 m length (Fig. 5). Tirpol consists of two parts. The upper part is connected to Kharpol and the lower part passes through a hole on the roof of the Askhaneh and is placed in the middle of the runner stone.
- The Koloosi is a hole in the middle of Kharpol where Kharpol connects with Tirpol as shown in Fig. 5.
- The Ghalandarak is a piece of spindle wood with square section on one side and cylindrical shape on the other to facilitate Tirpol rotation in Koloosi (Fig. 5). It acts like ball bearing and made of pine or walnut wood.
- The Pareh (Fig. 5) is a vertical blade with a 3 m length and 0.15 m width, connected to the Tirpol via Bahoos (a horizontal connector between Tirpol and Pareh). Pareh is made of pine or walnut wood.
- The Charkhbad (Fig. 4 Detail B; Fig. 5) is the collection of Tirpol and Parehs (6–8 Parehs) which rotates clockwise. It is made of pine or sycamore wood.
- The Peyvand (Fig. 8) is the lower part of Tirpol used to maintain the consistency of two stories of the windmill. It is easily damaged because it has to support maximum torque and tension.

#### Architectural features

**Surrounding walls** Parkhaneh contains three surrounding walls with the height of 4 m (Fig. 6). Two stepped walls were built with the thickness of 0.8 m to provide more stability for the windmill and facilitate access to the elements of the windmill structure for possible repairs. The third wall was built facing the wind with a 1–1.2 m opening which is named Darvazeh. The wind blows through Darvazeh and rotates the Charkhbad effectively by provid-

ing the required torque and creating a draft. Darvazeh is connected to the surrounding walls with wooden beams.

#### Accessories and related tools

- The Doshakh is a long-handled tool with two prongs used to stop the rotation of Tirpol by placing its crotch inside the Pareh and leaning its end against the surrounding wall which is presented in Fig. 4 Detail C and Fig. 7. It is made of pine wood.

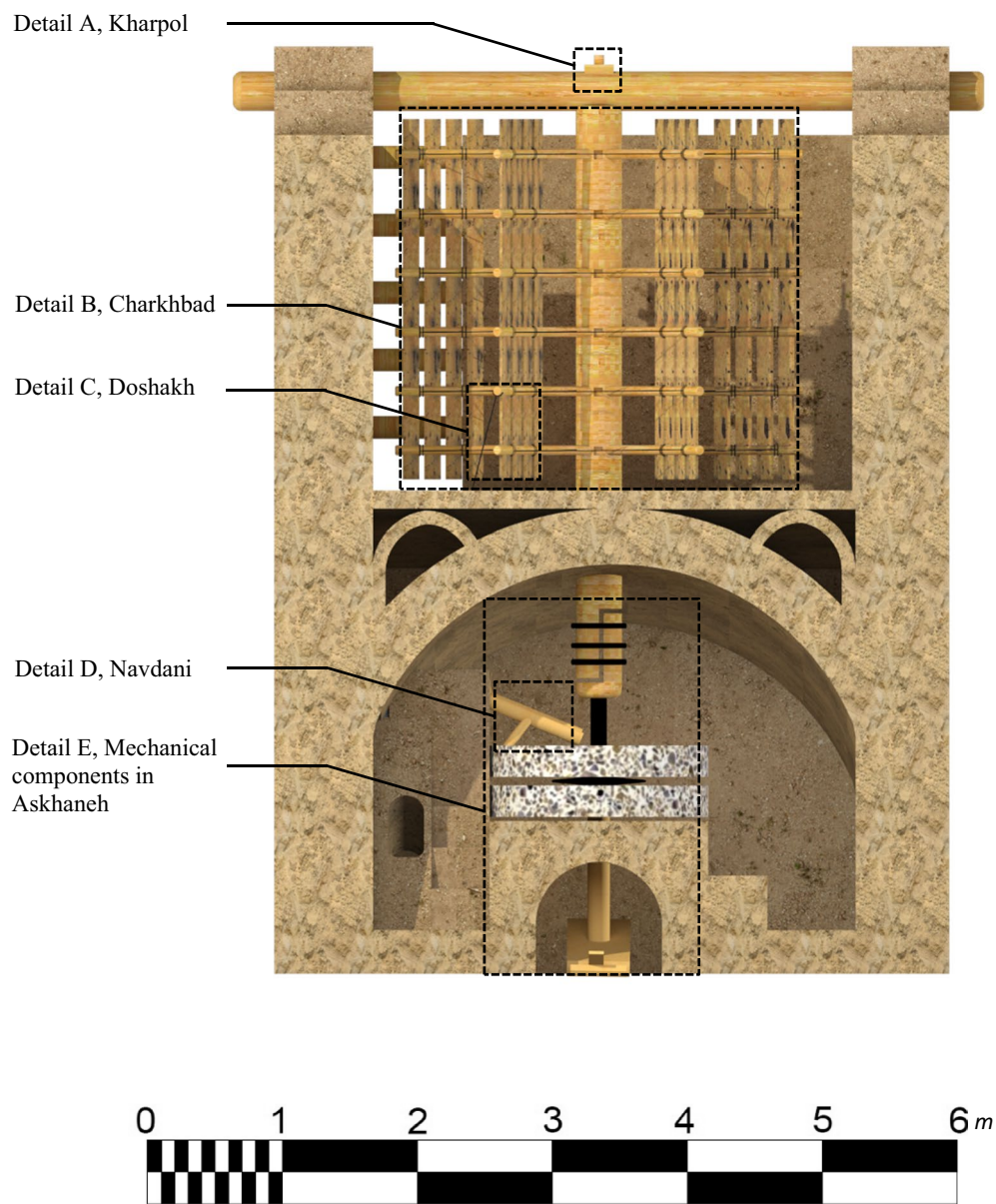
#### B: Askhaneh

In this section, each of the mechanical components and architectural features of Askhaneh will be discussed:

#### Mechanical components

The mechanical components of Askhaneh which is presented in Fig. 4 Detail E, include the runner stone, bed stone, Tavareh, Mosht, Takht and Varkesh. Each component will be described here:

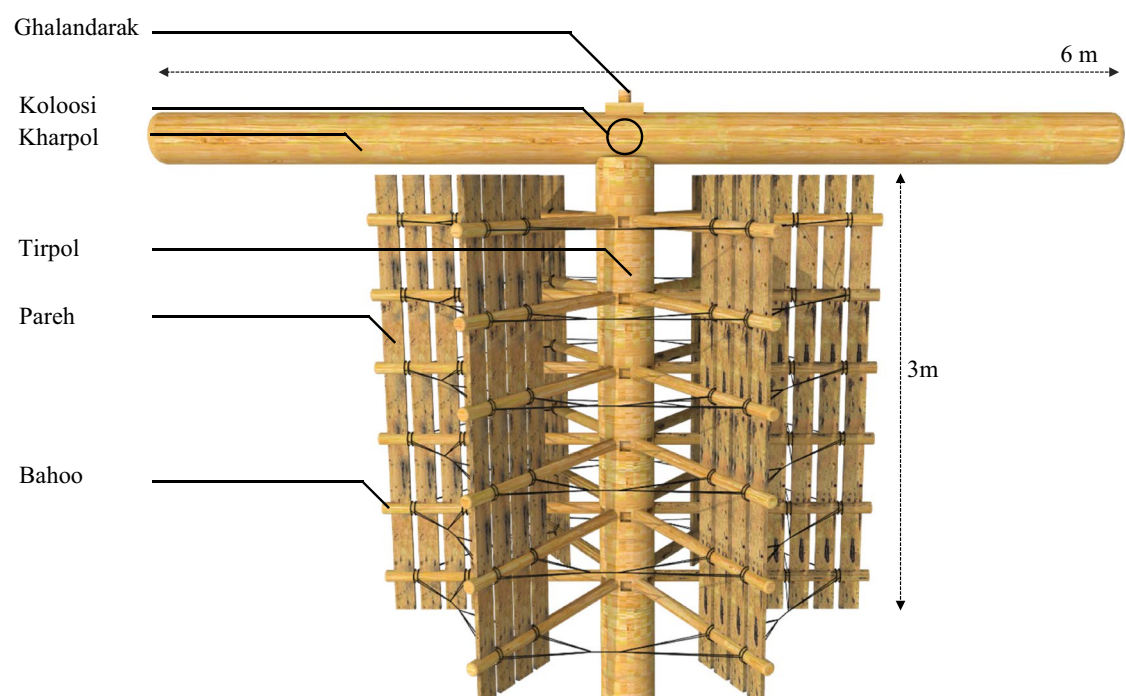
- The Runner stone is an upper concave millstone with a diameter of 1.4 m, spinning on the bottom stone, with a hole in the center, where grains enter (Figs. 8, 10). It is made of hard rock without veins.
- The bed stone is the bottom convex millstone with a diameter of 1.4 m, placed under Tavareh without any movement (Fig. 8). It is made of hard rock without veins.
- The Tavareh is a swallow-tailed or bow-tie component between two millstones. It facilitates the spinning of two stones on each other (Fig. 8). The length of Tavareh is 0.5 m and the width of it in the narrowest part is 0.06 m and 0.1 m in the widest part. It is made of metal.



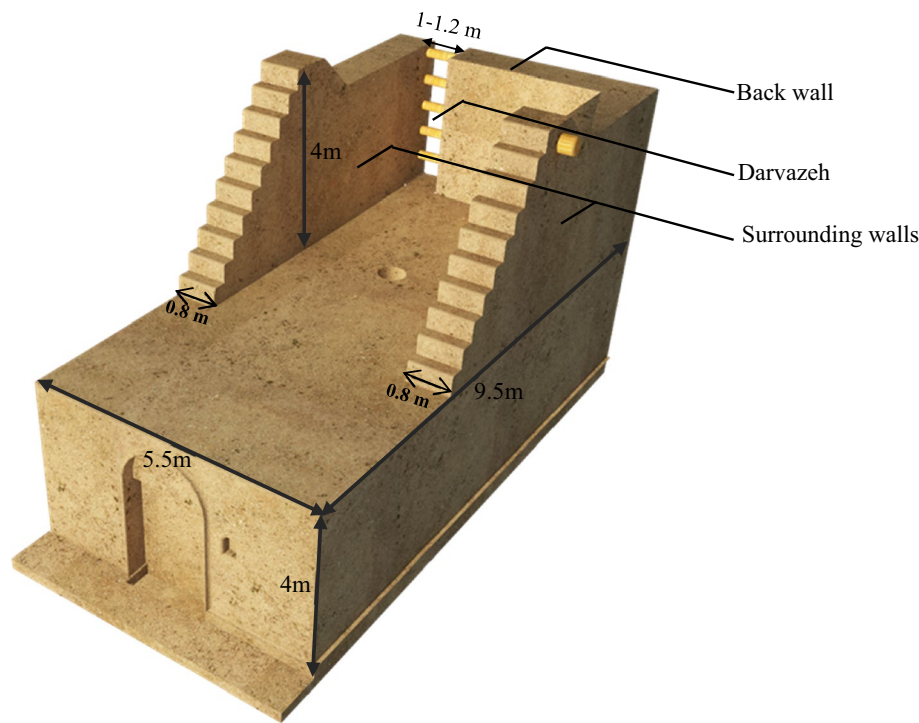
**Fig. 4** Cross-section of windmill

- The Mosht is a 0.4 m long vertical cylinder placed between Takht and Tavareh which is made of cedar or ash wood (Fig. 8). It transmits the compressive force created by miller's feet and applied to Varkesh to the Tavareh.
- The Takht (Fig. 8) is a support with 1 m length and 0.1 m width, located under bed stone and rests on Varkesh. It transmits the force of Varkesh to Mosht.

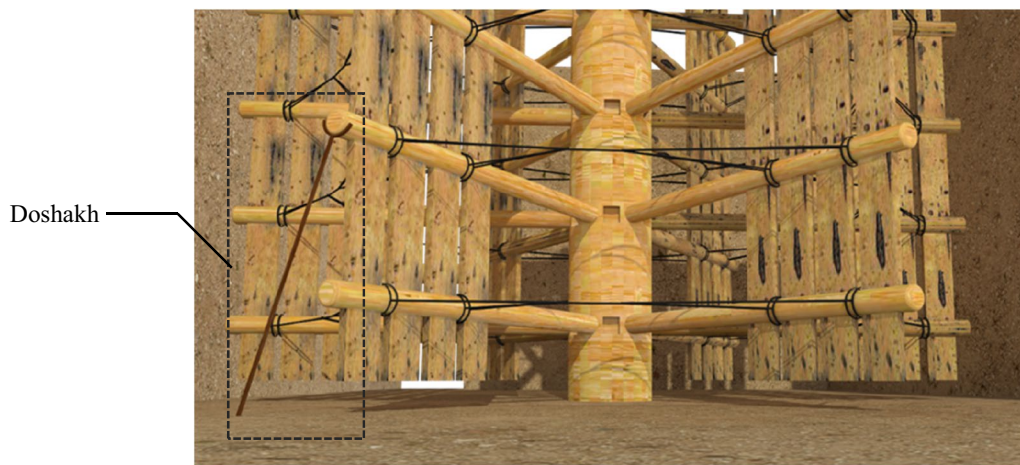




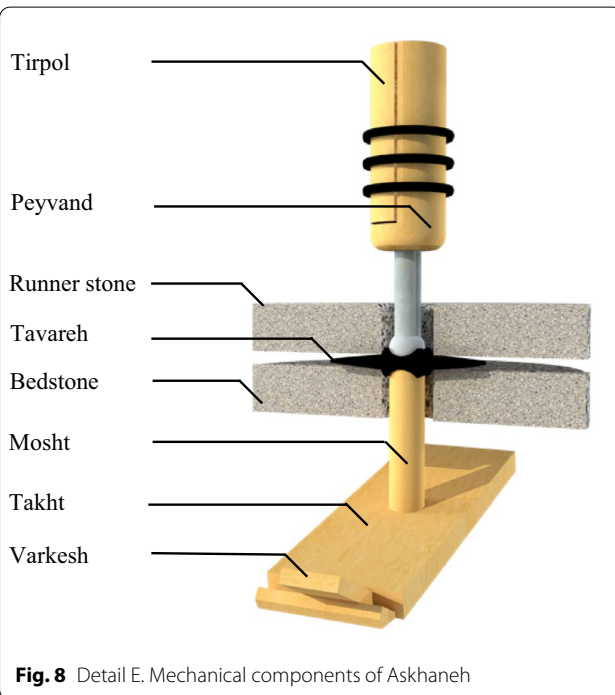
**Fig. 5** Detail A, B. The components of Charkbad and Kharpol



**Fig. 6** Architectural features



**Fig. 7** Detail C. Schematic view of Doshakh

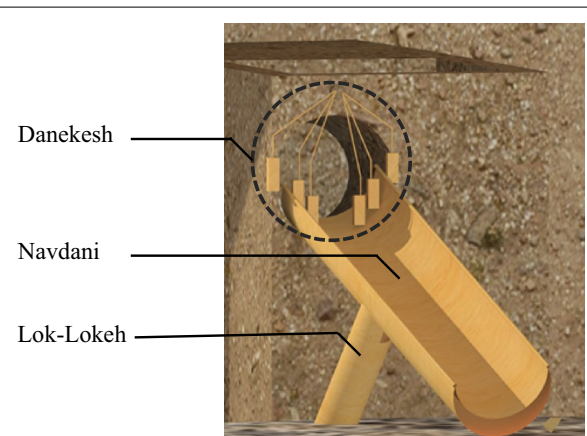


**Fig. 8** Detail E. Mechanical components of Askhaneh

- The Varkesh is a pedal, on which Takht rests, and acts as a lever by placing a stick under it (Fig. 8). Varkesh is made of wood or metal.

#### Architectural features

Askhaneh is a rectangular space with a length of about 9.5 m, a width of 4.5 m and a height of 4 m, as shown in Fig. 6. Askhaneh is entirely made of adobe and mud.

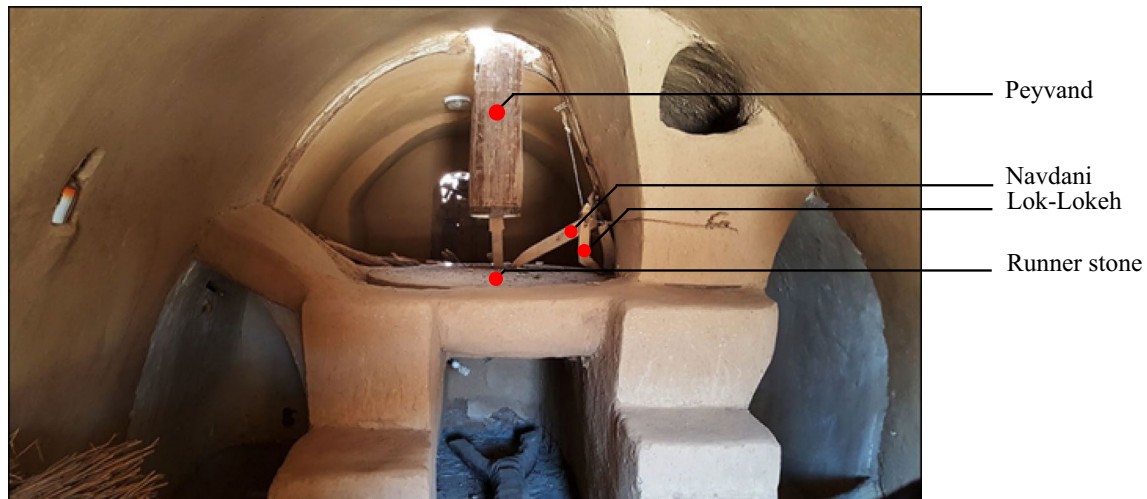


**Fig. 9** Detail D. Danehkesh

#### Accessories and related tools

- The Navdani is a 0.5 m length gutter used to carry wheat from wheat storage to the hole in the center of runner stone (Fig. 4 Detail D; Figs. 9, 10). It is made of metal or wood.
- The Lok-Lokeh is an oblique cylinder with a 0.4 m length on the runner stone and tangent to the Navdani (Figs. 9, 10). This cylinder is connected to wheat storage to control the amount of grain entering the Navdani with vibration. By increasing the rotation speed of Tirpol and the movement of the Lok-Lokeh, more wheat enters the mill. Lok-Lokeh is made of wood.
- The Danehkesh is a collection of wooden cubes which is shown in Fig. 9. Sometimes because of high vibration of the Lok-Lokeh, a huge amount of wheat enters the Navdani and the runner stone,





**Fig. 10** The interior of Askhaneh

which results in the overflowing of the wheats. Danehkesh is used to limit the amount of wheat entering the hole in the center of the runner stone. The number of Danehkesh in the Navdani depends on the wind intensity and the rotation speed of Pareh.

#### The operation of windmill

The windmill starts working by removing the Doshakh. The wind passes through the Darvazeh and makes the Charkhbad rotate. As the Charkhbad rotates, the upper part of Tirpol rotates in the Koloosi and the lower part (Peyvand) rotates in the runner stone and rotates the Tavareh. When the Tavareh rotates, the Lok-Lokeh starts vibrating. This vibration is transmitted to the Navdani and makes the wheat flow from the wheat storage to the Navdani and pours it into the runner stone, and then converts it into flour.

To stop the windmill, the miller places the Doshakh inside the blade and leans the end of Doshakh against the outer wall of the mill to stop the rotation of blades. Alternatively, the miller presses Varkesh, by which Varkesh is pressed upwards, and presses the Mosht to Tavareh which stops the rotation of Tirpol.

#### The relationship between architectural features and mechanical components

The effects of mechanical components on the architectural features can be described as follows:

- Kharpol transmits forces generated by windmill operation and the wind forces to the surrounding walls. In order to prevent any damages and maintain the stability of the windmill, the surrounding walls are built with a width of 0.8 m.
- In order to protect the mechanical components from erosion caused by the wind, two surrounding walls are built in stepped form.
- In order to convert kinetic wind energy applied to Tirpol in upper story to mechanical energy of the runner stone in the lower story, there is an opening on the roof of the Askhaneh where Tirpol passes through.

The effects of architectural design on the complexity of a mechanical system can be the following:

- The accurate placement of three walls in Parkhaneh intensifies and directs the wind energy. This is how the required force to move the mechanical components is provided.
- In order to provide the required torque and create a draft for the rotation of Charkhbad, an opening (Darvazeh) has been created in the third wall.

#### Conclusion

This paper investigated a windmill in Nehbandan which is an example of architectural heritage. Harnessing natural energy and using local materials such as stone, wood and adobe, the residents were able to create environmentally friendly structures. In this paper, one of these windmills

that is still standing in Nehbandan was selected from a chain of windmills. Then, based on architectural survey, interviewing with millers and sketching, the dimensions of architectural elements and mechanical components were obtained and the windmill was modelled.

The results reveal that there is a close relation between architectural features and mechanical components. The orientation of this windmill toward prevailing wind, the correct placement of walls in three faces and creating a hole named Darvazeh in the third wall to direct the wind into the Parkhaneh are architectural features which provide the kinetic energy of the wind to move the mechanical components. The stepped form of the surrounding walls prevents erosion of mechanical components and as a result increases the durability of the windmill. Creating a hole in the roof of Askhaneh for the passage of Tirpol has connected the mechanism of two stories by this mechanical component. This shows how architecture is affected by mechanics. Also, mechanical components like Kharpol lead to the stability of the whole set by transferring the forces generated by the operation of the windmill and the wind force to the surrounding walls.

It is suggested that conserving these architectural heritages, creating a 3D model of them and leveraging novel technologies such as augmented reality or virtual reality can assist in better understanding of cultural heritages.

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#### Authors' contributions

All authors have participated equally in 3D modelling, writing—original draft preparation, visualization, investigation, writing—reviewing and editing, methodology, architectural survey, supervision, validation, verification. All authors read and approved the final manuscript.

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#### Availability of data and materials

All data obtained during this study are included in this published article, and the 3D models (in.skp) are available from the corresponding author on reasonable request.

#### Declarations

#### Competing interests

The authors declare that they have no competing interests.

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