Reusing grain silos from the 1930s in Italy. A multi-criteria decision analysis for the case of Arezzo.

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Abstract

Italian grain silos from the 1930s are emblematic buildings of an historical period characterized by technological progress and particular economic and political conditions. Due to their unfavourable morphology related to the specific agro-industrial purpose, their conservation and adaptive reuse constitute a major challenge, even if supported by their historical, technological and, sometimes, even artistic values. For this reason, most of these buildings remained abandoned for a long time and are now affected by a serious material degradation. This study attempts to overcome the difficulties in selecting the best reuse proposal through a multi-criteria decision-making method. This approach makes it possible to effectively compare different scenarios and identify the most satisfactory use for the silos. The multi-attribute decision analysis applied to the case of the silo of Arezzo demonstrates its effectiveness and potential in the context of historic buildings.

Key words: adaptive reuse, grain silos, industrial heritage, multi-criteria decision making

1. RESEARCH AIMS

This study addresses the adaptive reuse of Italian grain silos built during the 1930s, a significant architectural heritage today largely unused. The selection of the most suitable use is a complex decision problem because of the coexistence of different objectives and several constraints, such as the preservation of the values of the silos, the interest of private investors and the needs of the community. The aim of this work is to identify a methodology to find the best adaptive reuse for grain silos by means of multi-criteria decision-making (MCDM) method. A significant step is the identification of a robust set of attributes which are tailored to a case study in Italy. Seven design proposals are evaluated by four decision makers and compared on the basis of 57 attributes, which are suitably defined in this work. In this way, it is possible to assess the effectiveness of MCDM for this particular typology of industrial architectural heritage.

2. INTRODUCTION

The high dynamism of our time and the rapid changes of our society, combined with a weak legal protection of more recent architecture, have been seriously threatening important elements from the heritage of the 20th century [1]. In particular, this regards industrial buildings, whose appearance is considerably far from the well-known appreciated typologies of the older heritage.

In Italy, the reference law for the protection of cultural heritage (i.e., the Code for the Cultural Heritage and the Landscape [2]) does not define specific conservation requirements for different heritage typologies, nor in relation to a specific era, it solely requires the buildings to be aged at least 50 years. A more detailed classification of eligible properties for preservation is provided by the Central Institute for Cataloguing and Documentation (within the Ministry of Cultural Heritage), which considers industrial architecture together with fortified and religious buildings, residences, rural buildings, infrastructure, and so on.

Since the late 1980s, many initiatives and international organizations such as DOCOMOMO International[1] stressed the aesthetic, technical and social values of modern heritage, thereby encouraging international debate about its preservation. They also highlighted the need for common methodologies and criteria to assess the significance of modern heritage and to identify values and intervention priorities, proposing shared approaches to conservation and reuse [3] [4].

Italian grain silos of the early 20th century represent a problematic typology of architectural heritage: highly

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[1] DOCOMOMO DOcumentation and COnservation of buildings of the MOdern MOvement.

function-specific industrial buildings mostly made up of reinforced concrete. They are worthy of preservation since they witness a particular period of the economic, rural and political history of Italy, and possess technological and, sometimes, aesthetic values. Nowadays, most of them are abandoned and are hardly adaptive to other uses due to their particular structural configuration, the material deterioration and because their location is often within marginal urban and social contexts. Besides, reuse is penalized by the negative attitude toward the memory of the Fascist regime and by the construction material itself (i.e., reinforced concrete) that exhibits an unfavourable aged aspect (as opposed to, for example, stone or brick masonry). Its repair typically requires innovative technologies and also high costs.

The research of a new use for these buildings can be eased and optimized through a multi-criteria decision-making (MCDM) method, whose application allows evaluating preservation aspects together with the compensative socio-economic advantages.

The first part of the paper introduces grain silos and the current challenges in their reuse, with particular attention to those of the 1930s. Then, a methodology for the selection of the best reuse proposal is developed, focusing on the MCDM analysis. The application to the case of Arezzo reveals the difficulties in approaching the adaptive reuse of these function-specific industrial buildings and highlights the potential of decision-support procedures for the grain silos typology.

3. MULTI-CRITERIA DECISION-MAKING ANALYSIS

A formal methodology to deal with complex decision problems is provided by multi-criteria decision-making analysis (MCDM), consisting of a set of techniques that aims to comparatively assess alternative projects or heterogeneous measures.

The earliest references relating to MCDM trace back to Benjamin Franklin [5-6] and to the mathematical contributions of Georg Cantor [7] and Pareto [8], who firstly studied the aggregation of conflicting criteria into a single composite index. Since then, thanks to the contributions of Operational Research, multi-criteria analysis was employed in different areas, deriving techniques from other mathematical disciplines, such as mathematical modelling, statistical analysis and mathematical optimization.

MCDM can be classified in two categories – multi-objectives decision analysis (MODA) and multi- attribute decision analysis (MADA) – in relation to the decision context and the complexity of the mathematical model [9-11]. The first type is commonly used to determine the optimal compromise solution with a probabilistic approach, which assumes continuous solution spaces. The second one utilizes a deterministic approach with a finite domain composed by a finite number of alternatives and requires multiple attributes to determine choices. MADA methods do not aim to compute an optimal solution; rather, they aim to determine a rank of decision alternatives that is optimal with respect to several criteria or optimal actions among the existing solutions. The main difficulties in the application of MADA are related to the definition of the attributes starting from the construction of a sound knowledge framework.

Recent studies [12] examine scholarly literature pertaining to decision analysis and identify the most common MCDM methods, which are multi-attribute utility theory (MAUT) [13-14], analytic hierarchy process (AHP) [15], fuzzy set theory [16], analytic network process (ANP), case-based reasoning [17], data envelopment analysis [18], simple multi-attribute rating technique [19], goal programming, ELECTRE [20], PROMETHEE [21], weighted-averaged sum (WAS), the technique for order of preference by similarity to ideal solution (TOPSIS), and additive ratio assessment (ARAS).

The widespread diffusion of MCDM in urban planning [22-25] is connected to the need of justifying policy choices and to the possibility of involving the community in the process. By providing quantitative data to solve a planning problem, it is an important communication tool within the decision-making body, the evaluators and the wider community. The method can be set up on a regional scale to locate high-impact constructions [26] or to compare environmental impacts and values [27-28].

Over the last few years, different MCDM have been applied for heritage assessment, but there is not a precise method preferably adopted. A common purpose is to rank alternative scenarios for reuse or enhancement of historical buildings and sites [29-31]. Other valuable applications in the management of cultural heritage allow grading different sites in order to identify investments and conservation priorities [32-35]. Many cases related to the reuse of architectural heritage are studied through MAUT, considering only qualitative attributes [36]. AHP and ARAS methods have been applied to define the priorities for the reconstruction and renovation of heritage buildings [37-38], considering the opinions of representative stakeholders of the decision problem. The AHP or TOPSIS grey methods have been applied to rank reuse alternatives for the upgrading of vernacular buildings [39], taking into account multiple quantitative and qualitative criteria and experts' opinions. Advanced studies developed a five-level project selection model based on ANP to prioritize a set of construction projects [40] or show the application of the fuzzy theory for the proportional evaluation of projects, thus considering the uncertainty in the assessment [41].

4. THE GRAIN SILOS OF THE 1930s

For a deep understanding of the values, distinctive features and reuse potentialities of grain silos of the 1930s, it is necessary to outline the origin of the typology and its development over the centuries in Italy and worldwide, moving thereafter to analyse Italian examples and their conservation issues.

4.1. Origins and development of grain silos

Long-term grain storage has been always one of the main actors in political and economic history since man created permanent settlements. In relation to climatic, environmental, economic and social conditions, storage facilities developed in different typologies, from old grain pits to current grain silos. Since the 12th century, specific masonry warehouses, the "Granges", spread throughout Europe thanks to monastic orders (e.g., in France, England, Belgium), showing fortified features in some cases (i.e. Cuna, Spedaletto and Montisi in Tuscany, Italy).

Between the 15th and the 19th centuries, grain reserves were stored in multi-storey masonry buildings, which were sometimes very large (e.g., "Granili" in Naples), while around the mid-19th century, innovative mechanized buildings – the so-called "grain elevators" – appeared in the major American ports to stock and move faster the shipped wares. American grain elevators even fascinated the leading members of the Modern Movement, from Walter Gropius [42] to Le Corbusier [43] and Erich Mendelsohn [44]. In fact, through the purity of their volumes, these buildings were able to express a new monumentality devoid of historical references, and to show the aesthetical and structural potentialities of the new construction technique: the "reinforced concrete" (Fig.1).

The introduction of machineries, powered first by steam and after by electricity, represented an actual revolution in grain storage buildings, so that mechanized grain elevators started to be built all over the world. Some important examples in Italy dating back to the 1900-1920s are in Genoa, Leghorn, Naples and Civitavecchia (the latter was unfortunately destroyed by bombing during World War II). In Italy, after the "Battle for grain" promoted by the Fascist regime, and with the introduction of the "collective grain storages" during the 1930s, the need to build suitable grain silos arose throughout all inland territories. Since 1936, the silos became the object of a systematic study among engineers, architects and many construction companies [45]. Actually, these buildings represent one of the first opportunities in Italy for the experimentation and the development of reinforced concrete in agricultural and industrial facilities as well as in the monumental architectures of Fascism. The situation was similar in other European countries, in particular Spain, where the autocratic policy was presumably inspired by the Italian model [46].

Italian grain silos were endowed with symbolic elements typical of Fascist architecture (such as 'littorie towers' and 'fasci littori') and formal features typical of Rationalist architecture. Thus, most of them should be preserved not only because of their historic and technological values but also for their architectural and aesthetic ones. Among the many examples, the most significant are the silos of Foggia (the widest in Europe at the time of construction), Rome, Venice and Piacenza, but many impressive cases were spread throughout all the Italian regions. Figure 1 shows images of the silos in Rome, Cagliari, Asciano di Siena and Gravina di Puglia.

Figure 1. From the left: 1) Silo of Port Arthur, Ontario Canada, 1910, historical postcard; 2) Silo of Thunder Bay, Canada [43, p. 27]. 3) Silo of Cagliari [51, p.96], 4) Silo of Rome [51, p.93], 5) Silo of Asciano di Siena, historical postcard, 6) Silo of Gravina di Puglia, historical postcard.

Sources about Italian grain silos are very fragmented. In Spain, instead, the documentation provided by the Servicio National del Trigo and the then Ministry of Agriculture for the Red Nacional de silos y graneros is very detailed and well known [47 - 49]. To date, in Italy, there are no lists or maps of the grain silos built under Fascism. One of the Authors of this paper is currently working on this topic and the work is still in progress [45]. Up to now, 71 silos have been identified by combining information from the coeval literature, local archives and other sources [50]. However, the total number of silos built under the regime is supposed to be much higher: previous studies [51] [52] mention that there existed nine hundred “facilities for grain storage” before Italy entered World War II, but this number might also include traditional warehouses.
Table 1 contains a list of the identified Italian silos with the respective sources. Which of them survived till today is not specified, since inspections are still ongoing.

Table 1. Location and sources of the identified Italian grain silos.

Piedmont	Lombardy	Veneto	Friuli Venezia Giulia	Istria	Emilia Romagna	Tuscany
Bra (I)	Bergamo (D)	Badia Polesine (B)	Cordovado (C)	Parenzo (A)	Bondeno (A)	Albinia (G)
Carmagnola (A)	Brescia I (I)	San Donà di Piave (C)	Latisana (A)	Umago (A)	Budrio (A)	Asciano di Siena (F)
Chivasso (I)	Brescia II (I)	Venice (B)	Pordenone (I)		Castel San Pietro (A)	Arezzo (H)
Novara (B)	Corbetta (I)				Cesena (E)	Castelfiorentino (B)
Pinerolo (I)	Desio (I)				Ferrara (B)	Borgo San Lorenzo (I)
Savigliano (I)	Gaggiano (I)				Fiorenzuola D'Arda (I)	Grosseto (G)
Saluzzo (I)	Landriano (I)				Medicina (I)	Prato (B)
Verolengo (I)	Lodi (I)				Piacenza (B)	Saline di Volterra (B)
Vigone I (I)	Paullo (I)				Pieve di Cento (A)	Siena-Grosseto (I)

Vigone II (I)	Rovato (C)				Rimini (E)	
	Sant'Angelo Lodigiano (I)				San Giorgio di Piano (A)	
	Solaro (I)				San Lazzaro di Savena (I)	
	Voghera (I)				Zola Pedrosa (A)	
10	**13**	**3**	**3**	**2**	**13**	**9**
Campania	**Puglia**	**Sardegna**	**Sicily**	**Umbria**	**Marche**	**Lazio**
Apice (I)	Foggia (B)	Arborea (I)	Porto Empedocle (I)	Città di Castello (I)	Ascoli Piceno (A)	Rome (B)
Avellino (I)	Gravina in Puglia (I)	Cagliari (B)			Castel di Lama (I)	
Benevento (A)					Jesi (B)	
Pesco Sannita (I)					Porto San Giorgio (E)	
San Bartolomeo in Galdo(I)					Porto d'Ascoli (I)	
					Urbino (G)	
5	**2**	**2**	**1**	**1**	**6**	**1**
source						
(A) R. Chapperon [53] (B) Federazione italiana dei consorzi agrari 1892-1952 [51] (C) F. Mariani [54] (D) Gavazzi, G. [55] (E) Garrè, G. [56]			(F) Azzini, A. [57] (G) Florence State Archive [58] (H) Historic Archive of Arezzo [59] (I) Other sources (Historic pictures and postcards, current pictures and newspapers)			

According to the coeval literature [53], it is possible to distinguish three main typologies among Italian grain silos: those with vertical cells, with floors and with hoppers (Fig. 2). The structure of the silos was mostly standardized: the overall height ranges between 20 and 30 meters, and the bins' dimensions vary between 4x4 and 5x5 meters. The staircase leading to the upper levels of the silos was usually placed in a part of the building called the turret, where the elevator was inserted. Horizontal conveyors were placed at the top floor and at the ground floor or at the basement level.

Deviations were usually not convenient due to the function and construction costs of the silos. The most convenient layout, both in the case of silos with vertical cells or with floors, was deemed to be with three rows of cells, each composed of four to six cells, with a capacity ranging from 3.000 to 8.000 cbm and an average area varying between 200 sqm and 400 sqm. With such dimensions, buildings could usually store from 20.000 to 50.000 quintals of product. However, there were some exceptions: much bigger silos were built in the main collection and distribution centres, such as the aforementioned silos of Rome, Venice and Piacenza, which were able to store more than 100.000 quintals, and the silo of Foggia, which had a capacity of 400.000 quintals and an average area of 3.600 sqm.

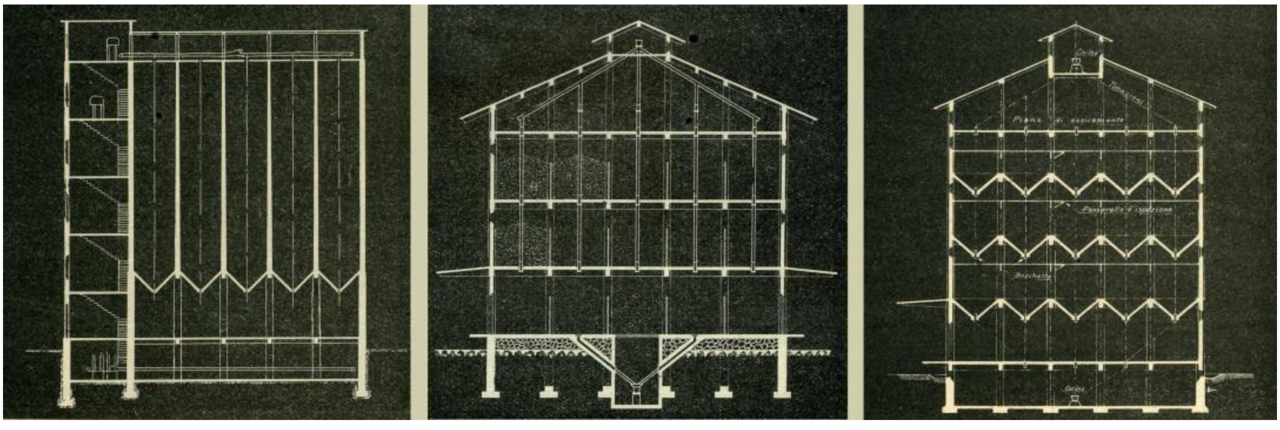


Figure 2. The three typologies of grain silos. From the left: silo with vertical cells, silo with floors and silo with multiple hoppers. [53, p.17,18,19]

4.2. Conservation and adaptive reuse issues

The majority of the existing Italian silos from the 1930s do not exhibit severe structural damages, except for localized cracks; however, the lack of maintenance following the silos' disposal usually affects finishing elements, surfaces and glazing systems. In Italy, most of them have been disposed, like the silo of Foggia, which has been threatened with demolition many times. Currently, only a few grain storage centres still use their old concrete silos, such as in Grosseto.

The first experiment in reusing silos is likely attributable to the Spanish architect Ricardo Bofill, who in the early 1970s transformed an abandoned cement factory in Barcelona into his head office. As for adaptive reuses of grain elevators, during the last decades, many were converted into student houses and apartment residences, such as the Mill Junction in the Newtown district of Johannesburg (South Africa), the Quaker Square Residence Hall for students of the University of Akron (Ohio), the Grünerløkka Studenthus in Oslo (Norway) and the Wheat Silo Apartments in Bunbury (Australia) [60]. Moreover, among the most interesting projects in the last decades, we can refer to the Seegmuller cereal warehouse in Strasbourg (France), originally built in the 1930s, and the silo in Fuentes de Andalucia (Spain), built in 1961 within the Spanish “Red Nacional de Silos y graneros”. The first one was rehabilitated between 2006 and 2008 and became the André Malraux Media Library; the second one was converted in 2010 into a cultural facility.

In Italy, only few adaptive reuses were carried out. In 2002, the silo of Rome was transformed into “Città del Gusto” [61] (the headquarters of the “Gambero Rosso” company), but unfortunately, this use has been recently moved to another site, and the silo has been disposed once again. The silo of Pieve di Cento (Emilia Romagna) was converted into a museum. A grain silo in Milan (not from the 1930s, but from the 1950s) was converted into an exhibition centre of the Armani's brand, and, finally, several competitions and workshops generated reuse proposals for the port silos of Genoa and Livorno, which, however, are still in a state of abandon.

The main challenges for the adaptive reuse of historical grain silos are the preservation of the original identity and the respect of the structural safety demand connected to the change of use. Indeed, the reuse might allow different and greater loads, while the materials, commonly deteriorated and obsolescent, may be unable to bear new stress regimes. Generally, new uses require modifications, such as the construction of floors and the demolition of existing walls for creating windows and doors. The two more widespread typologies of silos (fig. 2) in Italy – silos with floors and silos with vertical cells – can address the choice, allowing the identification of three main groups of eligible uses [45]:

- Residential, tourist and office uses are more suitable for silos with floors and openings on each level.
- Cultural spaces, auditorium and exhibition centres are suitable for both the typologies because they commonly require less openings.
- Storage uses such as archives, data centres, bicycle parking, luggage or food storages are highly compatible with the cellular structure of the vertical bins' typology, hence avoiding radical changes.

The choice of the new use is also influenced by the short-term and long-term economic sustainability of the project, so that it is important to examine the financial opportunities of private-public partnerships. Furthermore, new uses should be related to the needs of the territorial and local context, involving all the stakeholders right from the planning stage. Finally, the best reuse strategy cannot be defined without considering the conservation requirements.

Many researchers argue that adaptive reuse is a complex decision problem [62 - 64], taking into consideration economic constraints, historical and artistic value, environmental impacts, safety demand, and so on. Furthermore, multiple actors (such as public government representatives, architects, architectural historians, developers and owners) with different and conflicting objectives are involved in the decision process. Multi-criteria decision-making analysis can be a valuable methodology that, better than traditional approaches, can support the decision making of the adaptive reuse of Italian grain silos built in the 1930s.

4.3. A case study: the grain silo of Arezzo

Designed by the engineer Ubaldo Cassi on behalf of the Agricultural Consortium of Arezzo, the grain silo was built between 1937 and 1938 [65] in the Pescaiola district and remained in use until 2000, when the original area owned by the Consortium was sold to a private construction company that destroyed all the warehouses nearby. Only the active interest of both the academics and the community prevented the destruction of the grain silo. In fact, it was recognised as one of the first reinforced concrete buildings in the city, representing a great example of the rationalist industrial architecture of the Fascist period (Fig. 3) [66-67]. For this reason, in March 2006, the local Office for Cultural Heritage Protection finally designated the building recognising its cultural value [68].

Today, the grain silo is a private property and is located near the principal communication routes in the Pescaiola district, which over the last fifty years underwent rapid – and mostly by private initiatives – expansion. Ever since the cessation of the storage activity in the 2000s, several urban plans addressed the redevelopment of the silo, but while the unused building was increasingly deteriorating, the surrounding built-up area grew with residential constructions. In 2004, some citizens and associations promoted an assessment questionnaire to involve all the inhabitants of Pescaiola in the development of the district area [69]. The document reports the community’s satisfaction outcomes regarding public living in the neighbourhood and their opinion on intervention's priorities. On the basis of the data collected, the municipality provided several improving actions, consisting in a nursery, a small cultural centre and the regeneration of green areas. Nevertheless, the abandoned industrial buildings, including the grains silo, remained unused. Nowadays, 99% of the district area is urbanized [70] but presents many problems, such as a lack of social infrastructures, cultural activities and green areas and indiscriminate overbuilding and traffic.

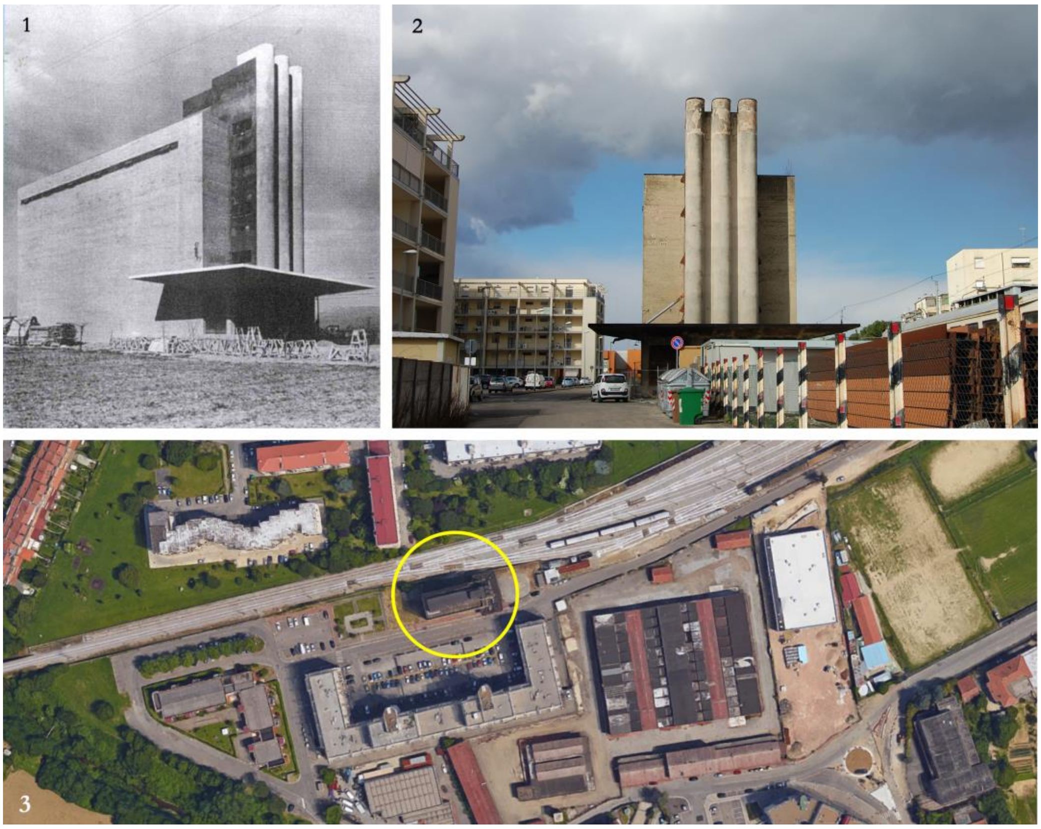


Figure 3. The grain silo of Arezzo (Italy). Historical (1) [29] and current (2) pictures of the building. Location and site plan (3).

5. MATERIAL AND METHODS

In order to set up a procedure for the selection of the most suitable adaptive reuse for grain silos, we adopt a case study, the silo of Arezzo, which is emblematic due to its features, the location and the architectural configuration. In the following, the first paragraph outlines the proposed methodology and the second one describes the application of MCDM.

5.1. The methodology

The proposed procedure tailored to the silo of Arezzo is organized into three macro-phases:

I. acquisition and processing of historical, urban, architectural and structural data regarding the grain silo and identification of the cultural values to be preserved;
II. development of different adaptive reuse proposals;
III. application of the multi-criteria analysis.

The first phase requires the gathering of archival documents, original preliminary and detailed designs, technical reports, architectural and structural surveys, urban plans.

The second phase is based on meetings with all the stakeholders, namely the Town Hall Technical Office of the Municipality, the building owner, the Office for Heritage Protection, the designers of the previous reuse projects, several community groups and neighbourhood associations. Besides, an important contribution to the definition of the reuse proposals comes from the results of the participatory process dating back to 2004.

Since the identification of new uses for the building should take into account both the economic and social aspects and the preservation of the historic, technological and symbolic values, paying attention to its peculiar functional identity, the definition of realistic proposals should take into account of the following constraints:

A. **Technical and economic feasibility.** The first depends on the potential unavailability of skilled labour, materials and technologies. The latter is related to the lack of adequate funding for the reconversion of the building.
B. **Reversibility**, namely, the post-project possibility of restoring the original state of the building according to the preservation perspectives and the status of the State-designated heritage.
C. **Structural, functional and aesthetic compatibility** that entails the respect of the existing building and its heritage value, avoiding major changes.
D. **Interest of the community** that allows to exclude the least preferred options and uses. It is assessed on the basis of the participatory process's results [69] and the data collected by the municipality's press office.
E. **Compliance with urban regulations and building codes**. Despite the lack of a preparatory plan for the silo, this sets forth only specific land uses and functions for the buildings in the area.

On the basis of meetings and the analysis of the documentation, the Authors have identified seven new uses which can be considered eligible for the grain silo. The design proposals are detailed in section 6 (Theory and calculation).

In the third phase, MADA is applied to rank different reuse options from the most preferred to the least one. At the first instance, each proposal can be considered equally valid in respect to the other ones. The most satisfactory use for the grain silo is selected encompassing the coexistence of different constraints and scopes as well as the opinion of a proper set of stakeholders of the process. Among all the stakeholders, the Authors selected four decision makers whose opinion was gathered both in a direct manner, through interviews and meetings, and via consultations and representative statistics.

5.2. Multi-criteria decision-making analysis for the reuse of the grain silo of Arezzo

Typically, decision-making experts set MADA according to the following steps.
1) Definition of the decision context and identification of the objectives that should be measurable,

specific, agreed upon, realistic and eventually time-dependent (immediate, intermediate or ultimate).
2) Identification of different options for achieving objectives.
3) Identification of decision makers and actors in the decision process who can provide significant contributions to the MADA both as expert consultants and as evaluators. Possible stakeholders may be people or institutions, that hold information or have interests, financial or otherwise, in the consequences of any decisions taken.
4) Definition of one or more criteria to follow in the expression of preferences by each decision maker.
5) Identification of attributes and sub-attributes, namely, indicators that allow comparison of alternatives. These must be measurable and reflect the wished performance in the sense that it must be possible to assess, at least in a qualitative way, how well a particular option is expected to perform in relation to the criterion.
6) Weighting and scoring. Weights indicate the relative importance of each attribute to the decision and compose the weights vector. Scores can be expressed in various ways (bullet point scores, colour codes, qualitative opinions), but each piece of information needs to be converted into consistent, numerical values. Numerical scores assess the expected performance of each option through scales that represent the relative strength of preference.
7) Summarization of the overall performances through the "performance matrix", where each row contains the weighted scores of each attribute against each option. Let $A = \{A_i \mid i= 1, 2, \ldots, n\}$ be the set of attributes, $B = \{B_j \mid j=1, 2, \ldots, m\}$ the alternative and $w = \{w_i \mid i= 1, 2, \ldots, n\}$ the weights vector. The result can be summarized in a n x m matrix D in which each element d_{ij} is the weighted score given by $d_{ij}=w_i \cdot a_{ij}$

$$D = \begin{bmatrix} w_1 a_{11} & \cdots & \cdots & w_1 a_{1j} \\ w_2 a_{21} & \ddots & \cdots & w_2 a_{2j} \\ \vdots & \cdots & \ddots & \vdots \\ w_i a_{i1} & \cdots & \cdots & w_i a_{ij} \end{bmatrix} = \begin{bmatrix} d_{11} & \cdots & \cdots & d_{1j} \\ d_{21} & \ddots & \cdots & d_{2j} \\ \vdots & \cdots & \ddots & \vdots \\ d_{i1} & \cdots & \cdots & d_{ij} \end{bmatrix} \qquad (1)$$

8) Data aggregation and examination of the results. This phase is characterised by the superposition and mathematical elaboration of the performance matrix. The principal difference among the main families of MCDM methods is the way in which this aggregation is done.
9) Make choices and feedback. It is a separate step because none of the techniques available, whether they are financial analysis, cost-benefit analysis or multi-criteria analysis, offer a formal judgment. The ultimate decision needs to take into account factors that cannot be evaluated (e.g., policy, changes).

According to the previous steps, the objective (1) of the MADA within the case study is the selection of the most suitable adaptive reuse proposal for the grain silo. Stating that the new uses identified during the phase II represent the options (2), the decision makers (3) are chosen among the stakeholders and represent all the important perspectives on the subject of the analysis (managers, politicians, planners, end-users). Based on the interviews and the questionnaires, we have identified four decision makers, namely the Municipality, the Office for Cultural Heritage Protection, the Inhabitants and the Users, since they are involved in economic, socio-cultural and conservation issues. Their assessment method is expressed by specific criteria (4) presented in section 6 for each decision maker. The attributes (5) shall be representative of a large number of grain silos in order to extend their validity to the entire category. The items have been organised on a hierarchical basis in requirements (5a), attributes (5b) and sub-attributes (5c), following the Italian guidelines on architectural design [71-72]. Besides, they are divided into two groups: the design phase, governed by cost and conservation criteria, which includes the necessary actions for the implementation of the design solution; the operative phase, which entails the positive outcomes of the project in terms of social, cultural and economic benefit. Weights (6a), that provide an order of relative importance among the sub-attributes, are reported as dimensionless values. In this case, we adopted a direct assessment technique which implies answering the question: how important is each sub-attribute for the objective of the analysis (namely the choice of the adaptive reuse)? Scores (6b) are directly assigned by decision makers who shall answer the question: how much each sub-attribute affects the design proposal?

The weighting and scoring phases make use of the opinion of the decision makers on the design proposals. In particular, two people of the technical staff of the Municipality and the Office for Heritage Protection, respectively, were directly interviewed and asked to fill in the MADA form. Instead, the assessment of the Inhabitants was simulated by the Authors according to the results of the participatory process [69], given the difficulties in directly gathering their opinion. Also for the User's opinion, a simulation was performed by the Authors on the basis of the periodical surveys and the indications provided by the Public Administration and its press office; the information suggested the preference of the citizens of Arezzo in large scale strategic development. Besides, a number of citizens was interviewed in order to validate the assumptions. The questions followed the format of the participatory questionnaire and aimed at understanding the interest in preserving and reusing the grain silo.

The weighted scores of the single design proposal compose the performance matrix (7) which determines the results in terms of preference. The final number of the matrices is equal to the one of the decision makers. The four performance matrices are processed through the most common and simple aggregation method, the weighted-averaging sum (WAS), theorised for the first time in 1967 [73]. The method provides, for each alternative, the weighted average of the scores and expresses preferences in a linear additive function. The best alternative is the one with the maximum score obtained after the standardization of all weights. Even though it is an intuitive compensative method, it does not admit interaction among the criteria, since it is based on the independent preference axiom [74].

The results of the MADA (9) are analysed and an indicator that takes into account the distance between costs and benefits is provided. Let C be the summation of the scores corresponding to the attributes of the design phase, and let B be the summation of the ones within the operative phase. The ratio B/C offers a measure of the prevalence of benefits over costs and is assumed as representative in the decision-making process.

$$I_j = \frac{\sum_{i=1}^{n} B_{ij}}{\sum_{k=1}^{n} C_{kj}} \quad (2)$$

where j=1,...,7 is the number of the design proposals, i=1,..., 41 is the number of sub-attributes of the design phase and k=42,…,57 is the number of sub-attributes of the operative phase.

6. THEORY AND CALCULATION

Case study development and analysis

This section applies the three macro-phases already summarized in section 5. The first part reports a description of the surveys and the identification of the values of the grain silo. In the second part each reuse design proposal is described in detail and a preliminary qualitative comparison is illustrated. The third part focuses on the application of MADA.

6.1. Phase I: the survey

The building has a rectangular layout (33.40 m x 12,70 m) with two clearly distinguishable portions (Fig. 4): the forepart or "turret" has six floors and accommodates the staircase, and there are two vertical elevators (placed in the semi-circular projecting volumes) and weighing machinery; the back part is composed by vertical storage cells (13 m high) of different sizes and capacity [Table 2].

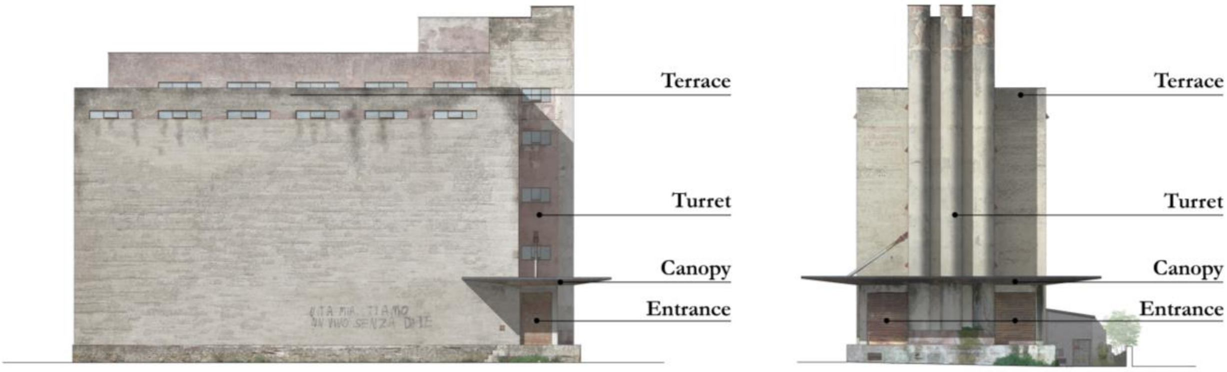
	Number	Shape	Height [meters]	Dimensions [meters]	Grain quantity [quintals]	Volume [m^3]
	12	squared	13	4,45x4,45	2150	257
	6	rectangular	13	4,45x2,95	1400	170
TOTAL	18				34200	4104

Table 2. The storage capacity of the grain silo of Arezzo. Vertical bins information.

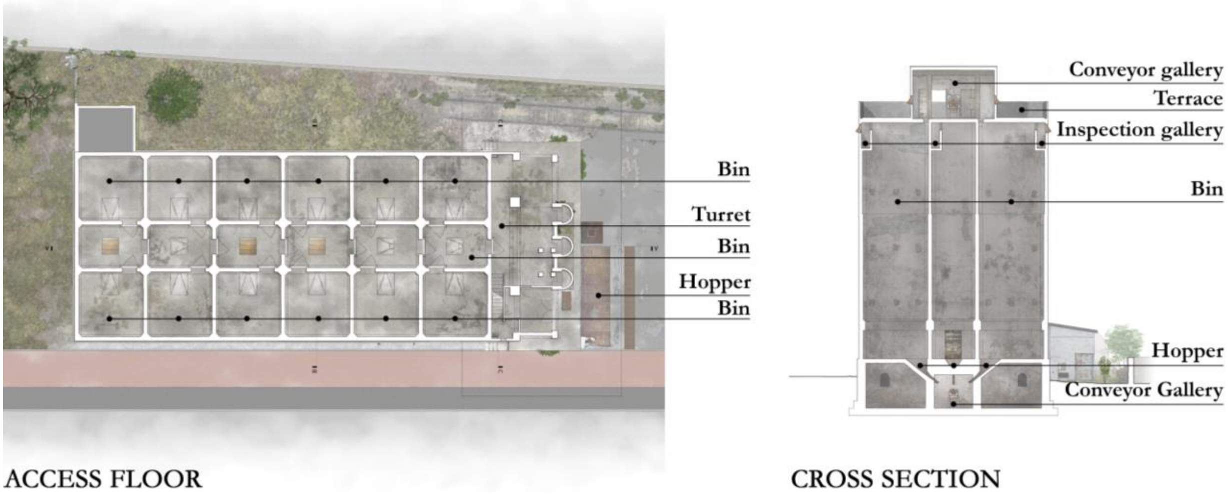
The incoming grain was poured in the basement, and, through a hopper, it was conveyed to the base of the vertical elevator; then, it was lifted to the top floor – the so-called “gallery” – which housed the superior horizontal conveyor that allowed the discharge of grain in the vertical bins. On the top floor, the grain could be properly dried on the terrace [46].

Despite the general good condition of the structural elements, the surfaces suffer from degradation; there are local damages, as concrete spalling and corroded reinforcing bars at the bottom of the cells as well as cracks at the interface between the bins portion and the forepart.

Many architectural values, such as the original writings on the façades, the surface finishing of the fair-faced structural elements, the canopy and the forepart are worth preserving (Fig. 5). These elements originate from the rationalist lexicon but were expressed by the designer in a singular way, reflecting a particular attention to details.



SIDE FAÇADE MAIN FAÇADE



ACCESS FLOOR CROSS SECTION

Figure 4. The grain silo of Arezzo (Italy). Architectural survey of the building.

Figure 5. The grain silo of Arezzo (Italy). Architectural and technological elements of the building. 1) Historical writing on the main façade; 2) Horizontal conveyor on the terrace floor; 3) Terrace floor; 4) Historical writing on the side façade next to the railway station; 5) Machineries on the terrace floor.

6.2 Phase II: the design proposals

The seven design proposals are defined by the authors using a scale of 1:200 in compliance with the previously defined qualitative constraints.

The detailed eligible uses are the following:

a) **Data centre**. Suggested by the Municipality, the design proposal is conceived as reversible and preserves the structural and functional configuration of the building. The proposal envisages new doors into the walls and new lightweight steel floors within the bins. The external façades remain unchanged, preserving the original appearance. This function is highly profitable and attractive for investors because of the growing demand for data centres, and the reuse of an existing structure could fulfil the scope to reduce costs of the transformation.

b) **Data centre with digital and didactic laboratories**. This might meet the residents' need of social infrastructures while providing a profitable activity. The two uses are separated, and the offices are organized in a new architecturally distinguishable side building. The external appearance is preserved, except for the rear façade where a new volume is provided. The inner layout is similar to the case (a) with the bins converted into server rooms.

c) **Paper archive**. In 2004, the municipality proposed the reuse of the building as a paper archive, but the design proposal remained at a preliminary stage. Starting from this idea, the authors designed a mechanized system for archiving, with only minor modifications to the façades. These highly versatile machines allow the vertical use of the cells, saving the realization of the floors and ensuring the maximum reversibility of the intervention. The construction of floors is limited to the central cells in which the traditional paper archive is located and accessible from each level. The upper level and the terrace host public spaces, such as a library and a study hall. The major problem to deal with is the ventilation system, the fire safety, in particular, the walls' resistance, and the protection measures for users and stored materials.

d) **Exhibition centre**. Given the symbolic value, the building could be adapted to an exhibition centre that aims to preserve the memory of the place and the rural past of Arezzo. Only a part of the bins is intended to be used as exhibition rooms, where new floors must be built; the remaining ones are used as accessible skylight wells. The circularity of the internal paths requires the construction of suspended passageways that make it possible to appreciate the scenic backdrop offered by the cell itself. Additional spaces are located within the turret, including meeting rooms and administration offices. The inner layout is altered in the central part by the construction of a staircase to connect three new floors. Because of the expected great presence of people, a new staircase is necessary as well as an emergency exit in case of fire placed next to the rear façade.

e) **Social housing**. Current trends in adaptive reuse [75-76] prove that abandoned buildings can be efficaciously redesigned into apartments to provide affordable housing. Besides the construction of new floors, the main changes pertain to the external side walls of the bins, mostly demolished to insert the windows. Nevertheless, the distinctive features are preserved, and the side walls are substituted with glass façades with textured surfaces to retain the historic character of the building. The terrace floor hosts common and public spaces, such as a nursery, meeting rooms, and study and leisure rooms.

f) **Thematic tourism facility**. This might be a viable perspective from a social, environmental and economic point of view. The design is reminiscent of the social housing proposal because of the need of new floors and new windows in the rooms and common services at the upper floor. However, the fire safety requirements are strict, so a new stairway is located in the rear of the building.

g) **Shopping centre**. Despite the great transformations' impact associated with new floors, doors and staircases, this proposal might be highly profitable for private investors and provide a meeting place for the community. Besides, the proximity to the main communication routes and to the railway station can include the building into the urban network. According to the proposed design, the façades are unchanged, but the inner layout of the building is altered by escalators, elevators and stairways.

At this stage, in order to stimulate debate, none of the possible functions were excluded *a priori*, even those entailing major modifications. The selection of four common variables (A = feasibility, B = reversibility, C = compatibility and D = social interest) that guide the design phase and encompass all of the defined constraints allows a preliminary qualitative comparison among the different solutions (fig.6). Only one of the constraints, the compliance with urban codes (E), was not considered as a variable because of the legal impact on the decision problem. As a result, some uses, and consequently design proposals, are skewed toward certain variables or actions.

6.3 Phase III: application of MADA

With reference to the elements defined in section 5, the objective (1) consists of the selection of the most satisfactory use among the set of the possible ones, while the alternatives (2) are the seven design proposals. The decision makers (3) with the corresponding evaluation criteria (4) are the following:

- The **municipality** emphasizes the technical and economic feasibility (highlighting also the importance to catch private investors), the compliance with urban plans and other regulations, the improvement of existing infrastructure and the ability to meet the needs of the inhabitants.
- **Inhabitants** focus on the utility of the new activities for the neighbourhood and on urban and environmental improvements.
- **Users** endorse the wide-ranging aspects of the functions, the presence of adequate support infrastructures and investment returns.
- The **Office for Cultural Heritage Protection** emphasizes the issues concerning protection and preservation of historical and environmental heritage.

The hierarchical scheme of the attributes (fig. 7) is composed by a total of 2 groups, 11 requirements, 23 attributes and 57 sub-attributes. The application to the case study considers only 37 sub-attributes due to the lack of reliable data at this preliminary stage and to the presence of the same action in all the design proposals.

The weighting system (6a) evaluates the sub-attributes in the interval (0, 1), except for those regarding the compliance with regulations, which always assume a unitary value. Furthermore, the scoring system (6b) ranges between -1 and 1, where the higher positive value is assigned to the sub-attribute in the case of maximum impact, and the lowest negative value is assigned to its maximum worsening. Finally, a value of 0 corresponds to any unchanged situation.

To clarify the weighting and scoring method, two examples are provided and explained in Table 3. As for the design phase, which includes costs, the sub-attribute 9 "demolition of walls" is considered. The weights assigned in this case by the Municipality and by the Office for Heritage Protection are equal to 1, because of the high costs of the action and its negative consequence on preservation, respectively. Inhabitants and users rate the same sub-attribute 0,7 and 0,6, respectively. The lower values refer to a weaker perception of demolition costs and to a limited attention to conservation. Conversely, scores are assigned in compliance with the ranges in Table 3 that limit their variability: zero corresponds to no demolition, values up to 0,5 are associated to the demolition of the internal walls, while the ones from 0,5 to 1 correspond to external walls' demolition. The four decision makers tend to give higher rates to the design proposals that present major changes of the external façade. Worth mentioning are the evaluations of the Office for Heritage Protection that provide a unitary score both to the social housing and to the tourist facility characterized by the radical and irreversible changes of the side facades; on the contrary, it assigns low scores to the proposals that entail the preservation of the existing configuration (0,1 for the paper archive and 0,2 for the data centre). The trend is the same for inhabitants and users even though their scores are lower, due to their different sensitivity to the sub-attribute of the design proposal, especially in relation to conservation.

As for the operative phase, which is related to reuse benefits, a significant example may be the sub-attribute 45 "employment effects". By prioritising benefits over cost, inhabitants and users assign higher weights (1 and 0,9 respectively) to the sub-attributes. The office for Heritage Protection provides a value of 0,6 while the Municipality 0,8; the latter, in fact, recognises the potential for job creation through the reuse of abandoned buildings. As regards scores, although decision makers tend to prefer their own suggested uses, they acknowledge the higher employment effects of certain design proposals than others. In fact, the data centre (with and without laboratories), the shopping centre and the thematic tourist facility obtain the highest scores from every decision maker. A particular case is represented by the assessment of the Office for Heritage Protection which is characterized by low values due to the lack of interest in the topic; however, the evaluation trend toward its proposal is confirmed, since the paper archive has the highest score of 0,2.

Table 3. Definition of the sub-attributes n. 9 and n.45 with their scoring system.

No.	Sub-attribute	Definition	Scoring system	
9	Demolition of walls	Takes into account the need to alterate/demolish existing concrete walls and the consequent conservation requirements.	0 = no alteration	1 = demolition of the external walls
45	Employment effects	Assesses the capability of each proposal to create new job opportunities for the inhabitants.	0 = weak capacity to create new job opportunities for inhabitants.	1 = high capacity to create new job opportunities for inhabitants.

The evaluation process led to the definition of overall weighted vectors composing the performance matrix (7) which was obtained by the application of the WAS; further details regarding the performance matrixes and the assessment of each decision maker can be found in the Supplementary Material. The result in terms of benefits/costs for each decision maker for the j-th proposal is I_j (equation 2), which is the ratio between the sum of the weighted scores associated to benefits (operative phase) and the sum of those linked to costs (design phase).

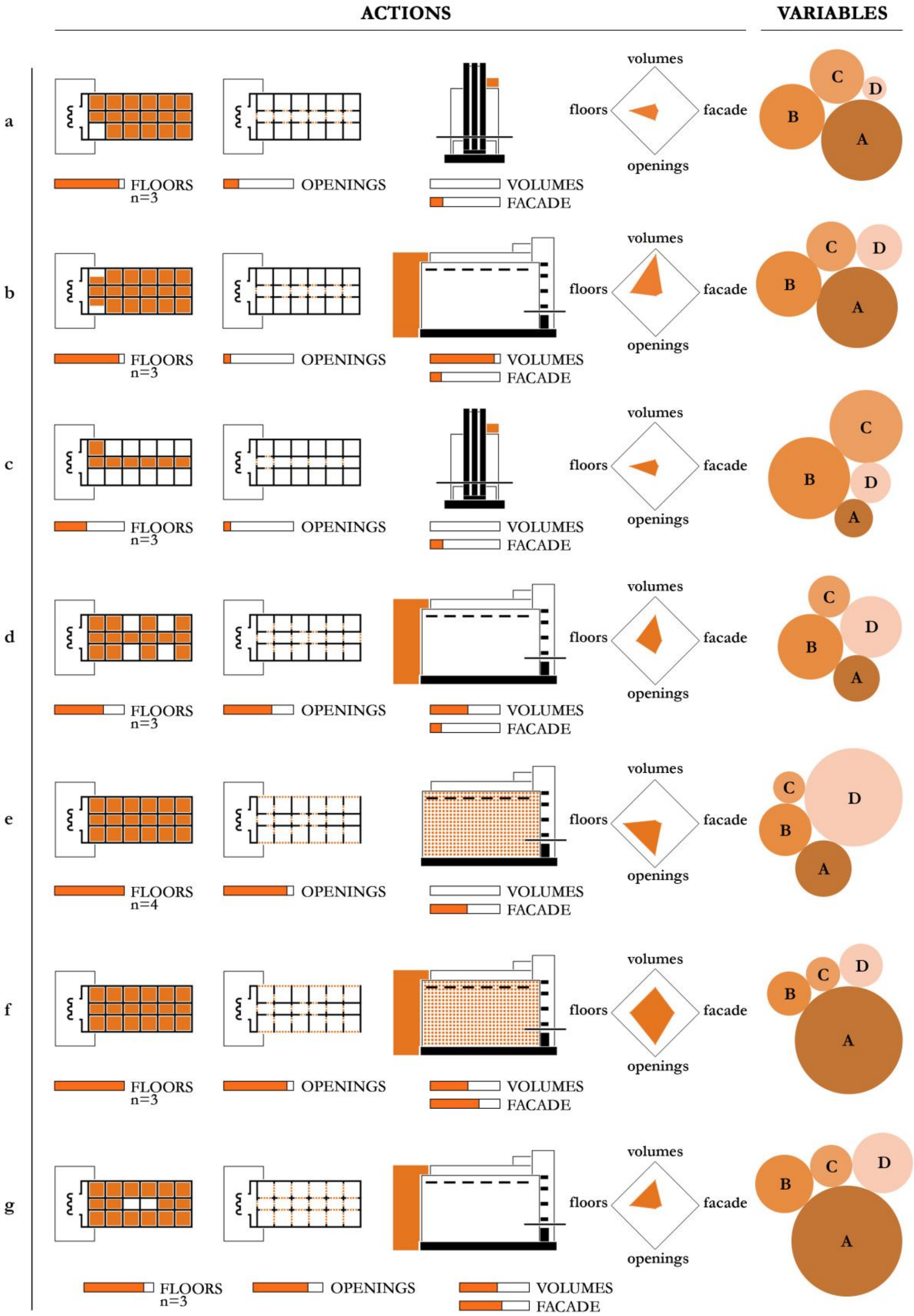


Figure 6. Design proposals for the grain silo of Arezzo (Italy). The seven alternatives are related to the transformation actions required to perform the new use (floors, openings, volumes, facade) and to the four qualitative variables (A = feasibility, B = reversibility, C = compatibility, D = social interest). The item “floors” is associated to the number n of new levels. The bar indicators show the impact of each action on the design proposal.

Figure 7. Tree hierarchic scheme of the macro groups with the attributes.

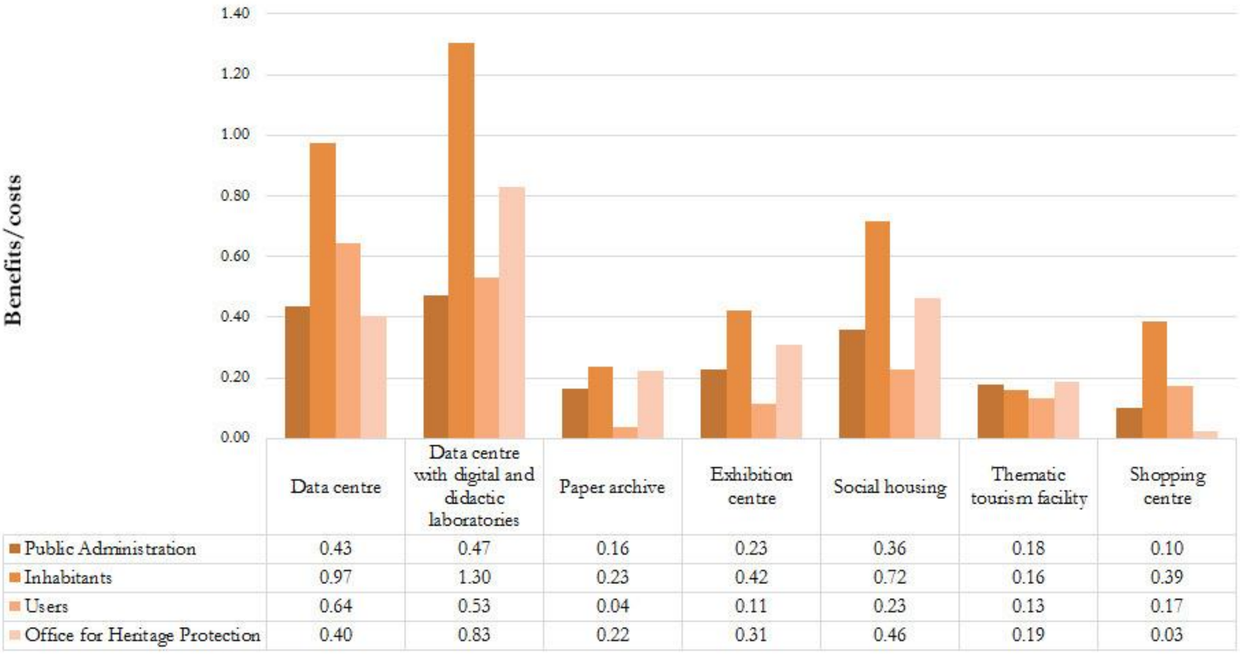
7. DISCUSSION OF THE RESULTS

7.1. Results of the MADA

By comparing the final data, it is possible to rank the preferences for the different alternatives for each of the decision makers and then to make quantitative considerations (Fig. 8). The analysis illustrates that the data centre with a digital and didactic laboratory has a higher benefits/costs ratio for all of the decision makers, except for the ‘users’, who gain greater advantages from the simple data centre. Instead, the presence of public services such as laboratories is a benefit for the residents and for the municipality. To summarize, the proposal is characterised by a highly compatible and reversible design, great economic potential and capacity to involve citizens in its use.

The less satisfactory proposals are the paper archive and the tourism facility: the first one, despite the high conservative nature of the design, is unable to ensure adequate interest for inhabitants; the second one, focusing on the tourist sector, does not solve the problems of the neighbourhood.

Finally, it is important to note that, due to the clear advantage of the data centre solution, there is no need to execute a sensitivity analysis on the weights that were adopted in this assessment procedure. Therefore, the results are to be considered robust with respect to the selected weighting criteria. In this case, the most satisfactory proposal is easily identifiable. Further assessment can be performed by using another aggregation method.



	Data centre	Data centre with digital and didactic laboratories	Paper archive	Exhibition centre	Social housing	Thematic tourism facility	Shopping centre
■ Public Administration	0.43	0.47	0.16	0.23	0.36	0.18	0.10
■ Inhabitants	0.97	1.30	0.23	0.42	0.72	0.16	0.39
■ Users	0.64	0.53	0.04	0.11	0.23	0.13	0.17
■ Office for Heritage Protection	0.40	0.83	0.22	0.31	0.46	0.19	0.03

Figure 8. Histogram of the preferences for the different alternatives for each decision maker. The rankings are expressed by the indicator benefits/costs.

7.2. The most performing design proposal

The design proposal for the data centre with digital and didactic labs is shown in detail in Fig. 9. This reuse may have a strong social impact because it provides public services that are especially intended for young people or companies (workshops and meeting areas). Moreover, the presence of the data centre including offices and technical facilities could interest private investors thanks to the expected high return of the investments. This could ensure the financing of the redevelopment of the area. Overall, this is a less profitable but important public function.

The public and private portions are independent and have separate entrances. The server farm occupies most of the bins, while the administrative area is located at a new construction site on the west side of the silo, next to the rear façade. The new volume is conceived to be separated from the existing building by means of a seismic joint, and the staircase connecting the terrace to the ground floor is an emergency route in case of fire. In fact, with the ability to host workshops and public activities, the terrace represents a place of assembly that requires even more attention in relation to fire safety. The entrance to the public area is located on the main façade of the building. The layout is organized in multi-functional spaces and meeting areas that are available for residents, local companies and start-ups. Moreover, specific digital laboratories allow undertaking innovative collaborations and promoting education, training and counselling activities.

Due to the lack of specific indications in Italy, the design of the data centre facility infrastructure follows American guidelines [77], which classify them in four “Tiers” related to various levels of risk and security. For the historical existing building, an intermediate risk level (i.e., Tier II) was adopted. This proposal requires new lightweight floors in the bins to sustain equipment and cables and the installation of a new staircase within the three cells near the entrance area. The stairway is conceived to be a scenic element that allows visitors to appreciate the majesty of the building and to understand its original use. As a result, a significant portion of the vertical cells was preserved, and all of the spaces were re-converted, minimizing the costs of the intervention.

8. CONCLUSIONS

The work focuses on grain silos of the 1930s, an industrial typology in the process of re-evaluation due to its significant historical memory, but characterized by a constrained spatial configuration, strong decay and marginal urban locations.

Stating the building typology’s values based on the formal and historical retrospective, the possibilities of reuse have been investigated on the basis of the examples of the international literature. In particular, the case of the silo of Arezzo was carried out under multi-criteria decision-making (MCDM) method, with reference to the multi-attributes decision analysis (MADA). The method has been applied on seven detailed design solutions, with four decision-makers and a great amount of attributes taking into account architectural, urban, economical, and conservation aspects. The optimal options resulting from this analysis are the two proposals with data centre, whose higher score, compared to the other alternatives, does not require the application of further aggregation models.

To our knowledge, this work presents the first application of MCDM analysis to grain silos. Even though other methods might be more accurate by considering the dependence among attributes, we adopted a simple WAS in order to focus on the definition of a great number of attributes and in order to easily verify their effectiveness. Thanks to its versatility and adaptability to different problems, the method is an effective tool to rank the most satisfactory intended uses for the whole category of the 1930s grain silos. A further research development could concern the analysis of a series of different case studies in order to define a general process encompassing attributes and decision-makers tailored on the typology. Besides, stating the simplicity of WAS, a more detailed analysis could adopt another multi-criteria method, considering the dependence between attributes and also probabilistic variables. The applied method does not consider the weight of the stakeholders, and its effectiveness might be compromised by the presence of a single decision maker stronger than the others, whose opinion heavily affects the choice. In fact, one decision maker may overweight its preferred alternative and bias the group decision. This might happen for economic and political reasons, such as, for instance, the financial contribution of a stakeholder who is interested in a specific proposal, or the public financing constrained to the achievement of a single socio-economic objective. Such situations are hardly predictable and could result in different choices, not supported by multi-criteria analysis. Similarly, the method cannot take into account how the funds are provided and the possibility to implement solutions in successive phases.

Nevertheless, this paper reveals the potentialities of MADA in the selection of a new use for cultural heritage buildings, addressing the complex decision-making process of the adaptive reuse and enhancement. In particular, the capability of the proposed methodology to be adapted to different contexts may offer the possibility to deal with the adaptive reuse of grain silos in any part of the world. In this sense, the present work may represent a starting point for further developments.

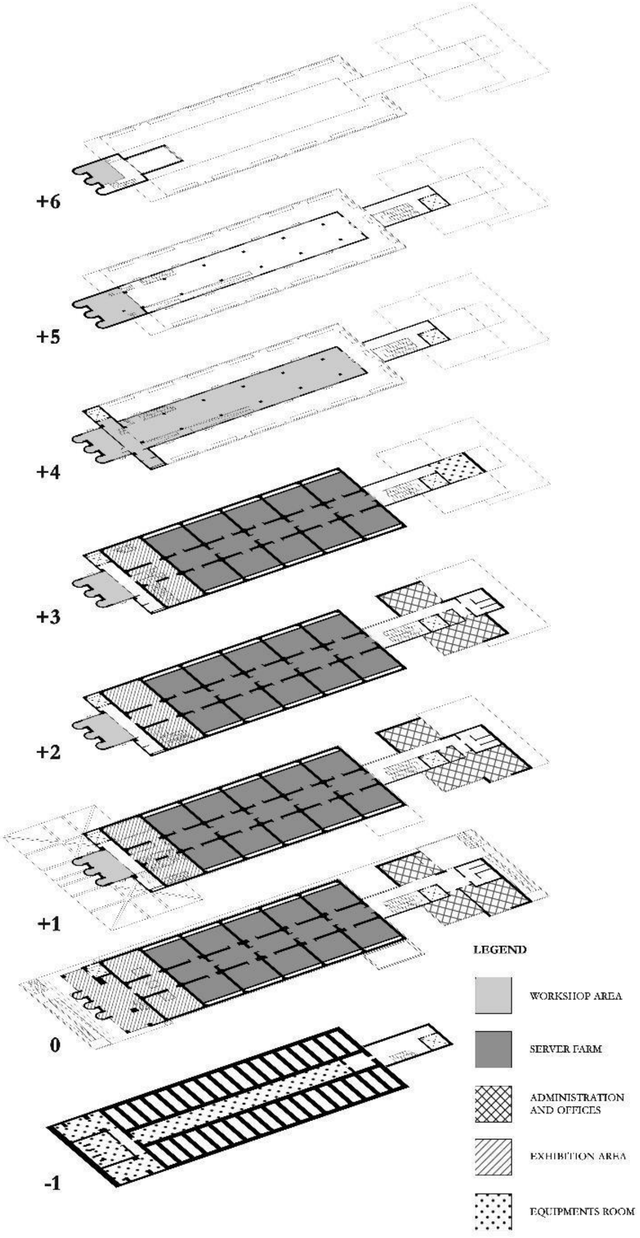


Figure 9. Details of the design solution for the data centre with digital and didactic labs.

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Figure Captions

Figure 1. From the left: 1) Silo of Port Arthur, Ontario Canada, 1910, historical postcard; 2) Silo of Thunder Bay, Canada [43, p. 27]. 3) Silo of Cagliari [51, p.96], 4) Silo of Rome [51, p.93], 5) Silo of Asciano di Siena, historical postcard, 6) Silo of Gravina di Puglia, historical postcard.

Figure 2. The three typologies of grain silos. From the left: silo with vertical cells, silo with floors and silo with multiple hoppers. [53, p.17,18,19]

Figure 3. The grain silo of Arezzo (Italy). Historical (1) [29] and current (2) pictures of the building. Location and site plan (3).

Figure 4. The grain silo of Arezzo (Italy). Architectural survey of the building.

Figure 5. The grain silo of Arezzo (Italy). Architectural and technological elements of the building. 1) Historical writing on the main façade; 2) Horizontal conveyor on the terrace floor; 3) Terrace floor; 4) Historical writing on the side façade next to the railway station; 5) Machineries on the terrace floor.

Figure 6. Design proposals for the grain silo of Arezzo (Italy). The seven alternatives are related to the transformation actions required to perform the new use (floors, openings, volumes, facade) and to the four qualitative variables (A = feasibility, B = reversibility, C = compatibility, D = social interest). The item "floors" is associated to the number n of new levels. The bar indicators show the impact of each action on the design proposal.

Figure 7. Tree hierarchic scheme of the macro groups with the attributes.

Figure 8. Histogram of the preferences for the different alternatives for each decision maker. The rankings are expressed by the indicator benefits/costs.

Figure 9. Details of the design solution for the data centre with digital and didactic labs.

Table Captions

Table 1. Location and sources of the identified Italian grain silos.

Table 2. The storage capacity of the grain silo of Arezzo. Vertical bins information.

Table 3. Definition of the sub-attributes n. 9 and n. 45 with their scoring system.