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Cultural heritage reuse applying fuzzy expert knowledge and machine learning: Venice's fortresses case study

Nicola Camatti [a], Giacomo di Tollo [b], Francesco Gastaldi [c] and Federico Camerin [d]

ABSTRACT

This paper presents a comparative analysis of two quantitative models for evaluating the reuse of cultural heritage, using fortified sites in a monofunctional city dedicated to cultural tourism, such as Venice, as a case study. The models explore three distinct reuse scenarios, assessing the appropriateness of each through a combination of fuzzy expert systems (FESs) and self-organising maps (SOMs). An FES acts as an expert-driven approach that formalises problem-solving based on external knowledge, while SOMs provide a data-driven perspective, autonomously processing and aggregating data without relying on external input or predefined assumptions. This innovative methodology facilitates the identification of new functional uses for cultural heritage by leveraging data sources related to the intrinsic structural characteristics of the assets, their territorial context and insights from external experts, alongside pre-established reuse scenarios that guide the analysis. In territories where public policies are fragmented and lack integration, this research provides a critical contribution by addressing the unbalanced distribution of functions across territories. The insights generated from this study offer practical guidance for stakeholders involved in managing cultural heritage, supporting enhanced institutional frameworks that can significantly boost the local economic complexity. This analysis showcases the potential of combining FESs and SOMs as a methodological advancement in the field of cultural heritage research. By illustrating how these tools can be applied together to address broader research challenges, the study contributes to the development of new procedures that can be adapted for use in similar contexts.

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1. INTRODUCTION

1.1. Adaptive reuse and its application to cultural heritage reuse

Preserving and appropriately utilising the built heritage of cultural and historical significance can be a pivotal resource for local sustainable development (European Union, 2020; Tweed & Sutherland, 2007). However, several challenges hinder this potential. These include limited financial resources for maintenance and conservation, difficulties among stakeholders in collaborating with private actors and insufficient emphasis on the role of civil and local society in microprojects for heritage conservation (Mangialardo & Micelli, 2018; Portolés Górriz, 2021). This inefficiency often results in underuse, abandonment or decay, making the identification of new strategies to reuse these assets and integrate them into urban agendas a priority (Mısırlısoy & Günçe, 2016).

In response to these challenges, since the 1970s the adaptive reuse of built cultural heritage emerged as a new field of policy and practice (Niemczewska, 2021). Adaptive reuse aims to assign a new, practical function to an unused or abandoned site (Mutal, 2005), creating opportunities not only for its conservation but also for meeting the needs of the local community and generating economic, environmental, social and cultural benefits (Gravagnuolo et al., 2021; Plevoets & Sowińska-Heim, 2018; Rodwell, 2008).

Successful interventions of adaptive reuse should simultaneously identify tools and strategies to instruct practitioners and designers to work at local and urban scale (Lanz & Pendlebury, 2022). At the local level, attention should be directed towards the intrinsic characteristics of the particular type of assets subject to intervention. At the same time, at the urban level, efforts should be made to fully leverage the synergies between the heritage and its surroundings (Galdini, 2019). These levels should embrace, firstly, a multi-stakeholder approach that incorporates a wider spectrum of perspectives, opportunities and needs into the process of reusing cultural heritage (Dell'Ovo et al., 2021). Secondly, such interventions should focus on holistic and multifunctional approaches to heritage conservation and reuse (Ginzarly et al., 2019; van Knippenberg & Boonstra, 2023). This can ensure greater adaptability to ongoing change and diversify opportunities and connections between different stakeholders, thus guaranteeing a sustainable and resilient future (Nasr & Khalil, 2024; Wang et al., 2023).

1.2. Research hypothesis, goals and contents

This paper explores the possibility of developing strategies for the reuse of cultural heritage assets to identify potential opportunities for reuse according to a multifunctional adaptive reuse strategy by researching the feasibility of a mix of new uses, using a quantitative model based on three main reuse scenarios: Attractiveness (i.e., reuse aimed at attracting tourist flows), Dissemination (i.e., reuse capable of producing and disseminating services and goods through on-site activities) and Territorial (i.e., conservative reuse, making the property available to the local community and civil society, preserving and enhancing its intrinsic and intangible values).

This paper aims to analyse these three options for enhancing cultural heritage, specifically focusing on Venice's fortresses and their unique characteristics within the socioeconomic context. It assesses infrastructural features, topographical distribution and historical value to inform multifunctional adaptive reuse plans. Unlike traditional studies evaluating monofunctional reuse projects, this research pioneers a holistic approach. It develops a methodology to assess individual and combined multifunctional reuse scenarios, addressing the feasibility of their integration. To achieve this, the study employs a quantitative method, combining multi-criteria decision analysis, fuzzy approaches and machine learning. This innovative approach contributes to a deeper understanding of fortress opportunities in Venice, offering valuable insights for sustainable and adaptive preservation within a long-term diversification strategy for cultural heritage enhancement.

In the frame of a limited attention given to fortress reuse opportunities, the paper makes two key contributions. Firstly, it provides a comprehensive inventory of fifteen fortresses in Venice, highlighting their current status, characteristics and future uses based on existing planning tools. Secondly, the paper introduces an innovative approach to identifying alternatives for reusing the fortified cultural heritage, underlining the valorisation of the intrinsic characteristics in relation to the potential of the surrounding territory in which they are located. This approach demonstrates how infrastructural characteristics, rather than topographic distribution or historic value, can drive multifunctional adaptive reuse plans, favouring integrated and flexible developments in line with the specificities of the surrounding environment.

The paper is organised as follows: Section 2 provides background information on the adaptive reuse of fortified heritage; Section 3 outlines the methodology; Section 4 describes the case study; Section 5 presents the application of fuzzy expert systems (FESs) and self-organising maps (SOMs); Section 6 discusses the results and reflects on the advantages/challenges of applying computational approaches to Venice's fortresses, drawing lessons from the study.

2. BACKGROUND

Since the early nineteenth century, fortresses across Europe have been gradually become obsolete and have suffered from the abandonment of their surroundings. Whilst sometimes these defensive artefacts began to be considered historical and cultural monuments (dos Santos, 2017), most of them were demolished in the name of hygienist operations to modernise cities related to the increasing speculative real estate operations. The emergence of military sites perceived as 'cultural heritage' spread over the second half of the twentieth century based on the 1954 'Hague Convention for the Protection of Cultural Property in the Event of Armed Conflict'. The following 1972 'World Heritage Convention Concerning the Protection of the World Cultural and Natural Heritage' included military heritage places such as the fortresses as 'tangible cultural heritage' (Klupsz, 2008), i.e., as physical artefacts that are produced, maintained and transmitted across generations in a society (Letonturier, 2019).

The end of the Cold War in 1991 marked a significant shift in the management of military sites, particularly fortresses built up to the early twentieth century. The abandonment of defence installations followed state-led programmes to restructure, modernise and rationalise the Armed Forces in line with geopolitical changes and austerity policies. These programmes embraced a neoliberal approach, emphasising deregulation, privatisation and competitive principles (Adisson & Artioli, 2020).

Christophers (2018) notes that the Ministry of Defence (MoD), as the owner, often retains disused land without initiating the land-use procedure for a change of purpose. This speculative action continues until the local authority is compelled to adjust land-use tools under conditions that are favourable to the owner, maximising profits when real estate market conditions allow (Camerin & Córdoba Hernández, 2023). In Italy, this state-centric approach is demonstrated by planning agreements mandating that 15% of the economic value from real estate market sales be allocated to the local administration (Camerin, 2021; Camerin, 2024).

The disposal policies coincided with efforts to designate fortresses as heritage sites, influenced by international organisations like UNESCO (1972; 2010; 2014) and state-led initiatives such as listed buildings in catalogues like the National Heritage List for England. Despite obtaining heritage status, scholars like Dallemagne and Mouly (2002) argue that military sites, including fortresses, are often concealed by the military apparatus for reasons of national security, limiting public access and knowledge. This lack of transformation hinders the effective conservation, preservation, and enhancement of military historic value, as well as the exploration of new uses for civil society.

Current literature focuses on two main aspects. Firstly, it emphasises how fortresses, owing to their historical roles as barriers, protection, command, depth, flanking and deterrence to defend cities and their hinterland, have evolved into unique physical elements within the contemporary territory. Due to their distinctive locations and physical forms, they play a crucial role as key components in the spatial organisation, connectivity and development of the territory (ICOMOS, 2020). Secondly, academics push for sharing expertise, promoting cooperation and emphasising the significance of fortified heritage to both build a common European history and redevelop these sites for new social, economic and spatial development (Navarro Palazón & García-Pulido, 2020). Particular attention is paid to the identification of new opportunities for the reuse to be placed at the centre of the cities' agendas and the generation and management of cultural tourist activities that can enable the spreading of knowledge and preservation of fortresses. These two contributions demonstrate that fortresses are distinguished by the coexistence of unique characteristics such as historical, tangible and intangible values, good localisation – very often close to natural and unbuilt areas that are easily reachable from the major logistic thoroughfares – and architectural structures equipped with large internal spaces and workshops able to accommodate the most diverse economic activities. Therefore, this set of characteristics enables fortified heritage to have various possibilities of reuse (De Seta & Le Goff, 1989). These opportunities are at the crossroads of multiple disciplines (i.e., archaeology, architecture, ecology, economics, history, mobility and urban planning) and, as happened in the successful case of the New Dutch Waterline, may contribute to sustainable economic growth, public tourism-related infrastructure and cultural attraction. The enablers for successful reuse should be based on a long-term scenario and go through successive steps: the creation of public awareness, knowledge of the past and local participation; the safeguarding of the cultural-historic values tied to the fortresses; the embedding of reuse in intergovernmental policies; the development of a financial plan and a widely accepted transformation plan (Verschuure-Stuip, 2020). However, mono-functional reuses appear to be the most common strategies according to three main strategies. Firstly, tourist-oriented reuses to exploit the history and unique natural context of fortresses (e.g., in Valletta-Malta; Ebejer, 2019). Secondly, business-oriented reuses based on innovative products and services, leveraging the distinctive creative-cultural, logistical and naturalistic environment of these places (e.g., the business district in the German Ingolstadt fortress,[1] and the luxury resort in Fort Beemster in the Netherlands[2]). Finally, preservation-oriented reuses based on the historical memory of these places through restoration and conservation interventions, without specific functional or productive uses (e.g., the French shelter 'ABRI' in Hatten[3] and Diest's Citadel and Fort Leopold in Belgium[4]). Current literature also focuses on three less predictable factors to take into account when developing the reuse: the delicate equilibrium of vegetation presence in preventing and facilitating the reuse of fortresses (Pardela et al., 2022); the growth of military heritage tourism (Venter, 2017); and the opportunities to create new economic flows based on greenery solutions for enhancing recreational areas (Zaraś-Januszkiewicz et al., 2020). These assumptions confirm that fortresses may be feasible places for a diversity of new uses, and not just to convert into single-function assets. These beliefs consequently reinforce the notion of fortresses as potentially flexible assets capable of achieving the broadest range of local development goals to pursue through the sustainable exploitation of cultural heritage (Panzera, 2022). The increasing awareness of the potential and diverse reuse options for fortified heritage is supported by extensive design experiences. However, these three types of reuses and factors often concentrate on the fragmented valorisation of specific reuse opportunities, rather than integrated and multifunctional strategies (Ebejer et al., 2023).

The aforementioned reuse possibilities align with those identified by Pflieger and Noya (2005) and Russo et al. (2006), recognising three fundamental scenarios of tangible cultural heritage reuse. The first is the Attractiveness scenario. It regards the transformation of cultural sites into desirable destinations for both national and international visitors and tourists. The objective is to enrich cultural heritage by optimising its appeal to the tourism sector. This scenario focuses on implementing rehabilitation measures for cultural heritage, ensuring appropriate services and infrastructure to accommodate and attract new tourist flows. The focus of the new activities is specifically on improving tourist services and promoting entrepreneurial ventures related to catering, rather than prioritising cultural, naturalistic, sports and recreational tourism. The second scenario is Dissemination. It consists of turning cultural sites into places where new businesses can be set up to produce goods and services. In particular, cultural heritage assets combine aesthetic dimensions and utilitarian functionality that can be a lever for the production of products. In this scenario, reuse interventions are designed to create favourable conditions for the creation of new cultural products and services that can be exported and disseminated outside the local territory, in order to attract new businesses. These interventions therefore provide both hard infrastructure (i.e., spaces, equipment and technologies) and soft infrastructure (i.e., organisation and management). Finally, the Territorial scenario consists of enhancing cultural sites as repositories of memory and custodians of local values. Cultural heritage has the capacity to act as a disseminator of values and a place for the social vitality of local communities. In this scenario, cultural heritage is configured as a 'social capital' capable of promoting social integration. In this context, reuse interventions aim to conserve and protect the cultural heritage to enhance its historical-cultural values and encourage its use as a place of memory and social integration.

3. METHODOLOGY

The selection of the appropriate method for this study involves evaluating two main categories of approaches: (i) those that integrate expert knowledge into the problem-solving process and (ii) those that autonomously process and analyse data without relying on external input or predefined assumptions (Grimaldi et al., 2025; Hudson, 2003). To represent these categories, two computational models have been chosen for evaluating potential reuse: fuzzy expert systems (FESs) for the expert-driven approach and self-organising maps (SOMs) for the data-driven approach.

An FES utilises fuzzy logic, applying membership functions to represent the degree of truth for logical propositions within a specific domain, with values ranging from [0,1]. These membership functions are defined based on expert judgments, partitioning the input variables into zones corresponding to qualitative features. This makes FESs particularly useful when expert knowledge is available and can be systematically formalised. In contrast, SOMs are machine learning tools that identify patterns directly from the data, without relying on any external knowledge or predefined structure, making them ideal for uncovering latent patterns and relationships within the dataset.

The focus of this study is to assess the applicability of these two approaches in addressing cultural heritage reuse problems. Specifically, it aims to compare the effectiveness of an FES, which integrates expert knowledge, with SOMs, which analyse data patterns autonomously. Although a more extensive experimental analysis of different methods and parameter configurations is beyond the scope of this research, this paper prioritises an initial evaluation of these two methodologies.

The application of these models relies on the guidelines established by di Tollo et al. (2012) in an attempt to contribute to the broader literature on clustering techniques (Mingoti & Lima, 2006). Both methods are used as stand-alone solvers, operating independently with no hybridisation. Neither model serves as a subroutine for the other, nor are their principles intertwined. However, the outputs produced by each method are compared to identify any points of convergence or complementary insights. Specifically, the independent application of an FES and

SOMs can yield valuable insights by leveraging the strengths of both approaches. This integration aims to establish a more robust framework for decision-making in cultural heritage reuse. Such a combined approach improves the accuracy of results and ensures that expert knowledge effectively informs data interpretation while revealing patterns that may not be immediately evident through expert analysis alone.

The broader issue of balancing expert-based remedial approaches with fully autonomous data-driven models will be examined in greater depth in the discussion and conclusions section. This section will explore the implications of using each method and their potential synergy in the context of cultural heritage reuse. The aim of this study is to identify which fortresses reuse strategies are preferable, focusing on their intrinsic characteristics, in particular their structural and functional qualities, the territorial context in which they are located, and a set of alternative reuse scenarios. Figure 1 illustrates the analytical framework proposed to achieve this objective. It is carried out in five phases, which together allow an analysis of the technical-functional feasibility of reusing fortified assets, based on a set of three pre-defined reuse scenarios.

The methodological approach developed combines multi-criteria decision analysis (MCDA) with the involvement of expert groups in the criteria identification and weighting phase (Keseru et al., 2021; Yau, 2009). In particular, this approach is enhanced by the use of fuzzy expert systems (FESs) and the application of artificial neural networks (SOM) to achieve the final result, which links the measurements of each fortified asset with the set of pre-established scenarios.

MCDA is a method that elicits and makes explicit the values and priorities of decision makers. In its various versions, MCDA is capable of processing data in diverse formats, such as qualitative and quantitative, and handling uncertain data (Fauré et al., 2017). Widely validated, MCDA evaluates preferences in complex decisions, with a focus on decision-making processes involving multiple pieces of information and conflicting objectives. By prioritising alternatives according to their suitability for stakeholders or expert evaluations through criteria scoring and weighting (Vögele et al., 2023), MCDA establishes itself as a reliable approach for addressing complex decision-making challenges in various applications.

The involvement of experts in the evaluation phases is proving to be valuable in achieving more informed and legitimate decisions (De Vente et al., 2016). Nevertheless, this form of evaluation faces the inherent challenge of assessing site characteristics, which requires reliance

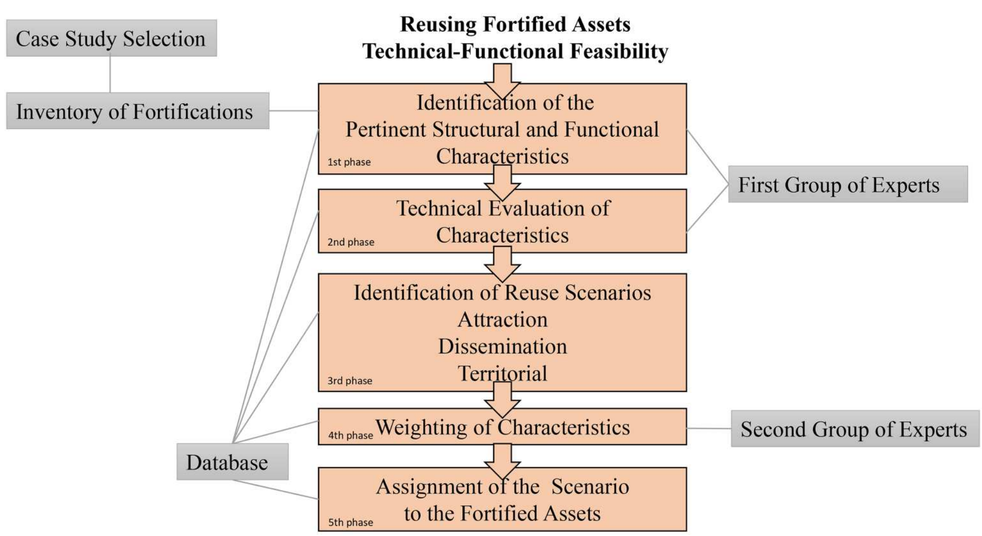

Figure 1. The phases of the methodology.

on the subjective estimates of experts (Pinero et al., 2017). To overcome this problem, this study uses an FES, which is based on fuzzy logic and is capable of transforming qualitative (and subjective) information into quantitative measures without assuming any underlying data distribution. In its basic formulation, an FES allows the user to solve complex, ill-defined and intractable problems (Tsekouras, 2007) and can be successfully used when dealing with noisy and imprecise data, as it is suitable for processing both qualitative (i.e., verbally defined) and quantitative data. The use of an FES is therefore recommended for dealing with non-linear data, and they are suitable for integrating external (i.e., expert) knowledge. However, the integration of FESs into regional studies remains limited (Hudson, 2003; Munda et al., 1994; Peck, 2003; Tomaney & Ward, 2000).

An FES not only helps to determine the suitability of a site for a given reuse scenario but also allows us to assign values that represent the degree to which a site can be associated with each of the scenarios (Peckol, 2021). The application of SOMs serves as an additional tool to determine the pairwise association between fortress and scenario, used to validate the robustness of the associations obtained through a purely data-driven approach (Kohonen, 1990). The initial phase of the proposed methodology involves identifying the pertinent structural and functional characteristics essential for analysing the technical-functional feasibility of reusing fortified assets. This process is conducted with the assistance of a group of experts. This group is composed of independent experts selected for their expertise and knowledge of the topics and issues under consideration (Sharpe et al., 2021). The group is tasked with collaboratively developing a comprehensive list of characteristics (criteria) for conducting the feasibility analysis study (Wang & Zeng, 2010). To compile a comprehensive list of characteristics, the group of experts is provided with preliminary technical documentation essential for reconstructing the attributes tailored to the specific case of the cultural asset under examination. The exhaustive list of characteristics used in this study is detailed in Table 3. It includes aspects related to the general state of conservation of the assets; the quality of their infrastructural, logistical, environmental and accessibility facilities; the presence of landscape, cultural and recreational resources; and lastly, the availability of data, information and official documentation to support the assessment of the assets.

The second phase involves the technical evaluation of characteristics within the inventory of fortified assets targeted for exploration. This phase aims to formulate an assessment regarding the degree to which each asset in the inventory of fortresses under analysis possesses the specific characteristics identified in the prior phase and evaluates its qualitative status. This evaluation is conducted by the same group of experts that compiled the list of characteristics (Tarragüel et al., 2012). These assessments take place following on-site inspections and rely on the official documentation issued by the competent local public administrations.

The third phase focuses on the identification of the Attractiveness, Dissemination and Territorial reuse scenarios. This process evolves from the recognition of the aforementioned main practices of fortress reuse at the European level, by capturing the synthesis of the three different options for functional reuse of cultural heritage proposed by Pflieger and Noya (2005) and Russo et al. (2006).

The fourth phase aims at weighting the importance of each characteristic – identified and evaluated in the previous phases one and two – for the realisation of the scenarios. The assignment of importance weights to each characteristic for scenario creation is conducted by a second group of experts following MCDA practices (Ribeiro et al., 2013). This approach aligns with studies specifically undertaken for the selection of cultural heritage reuse options (e.g., Dell'Ovo et al., 2021). Two main arguments support this approach: expert participation in MCDA promotes consensus, social learning and transparent decision making (Keseru et al., 2021); assigning weights based on expert experience improves model accuracy in suitability modelling, emphasising the need for different expert groups to ensure a comprehensive analysis of different aspects of the problem (Cucco et al., 2023).

Like the first group of experts, the second group comprises professionals with expertise and knowledge of the topics and issues under analysis, and includes a diverse mix of academics, technicians and stakeholders in the target area. This varied composition ensures coverage of different knowledge bases and sensitivities. The selection of experts is aligned with the specific analysis objectives (Sharpe et al., 2021) and aims to bridge the gap between research findings and implementation (Banister & Hickman, 2013).

Each member of the group works independently (Munda, 2004) and is provided with a questionnaire. The questionnaire includes an introduction explaining the interview's purpose, a list of various characteristics identified in the previous phase, and a request for the interviewee to assign a value, indicating the importance of each characteristic for the realisation of each of the three reuse scenarios considered. Details on the questionnaire administration technique and rules on the processing of personal data adopted in this study are provided in Section 5.1.

Once the questionnaire has been completed, the data are stored in a database for the subsequent analysis envisaged in the fifth phase, which aims to assign reuse scenarios to each fortified asset based on the set of assessments collected in the previous phases. The assignment is made using an FES to manage the ambiguity and uncertainty of the questions and answers that involved the different groups of experts. Artificial neural networks are also used to reliably verify the results.

The computational exercise aims to assign each observation (i.e., fortress) to a specific cluster (i.e., the Attractiveness, Dissemination and Territorial reuse scenarios). A plethora of methodologies can be employed to achieve this objective, with numerous contributions seeking to undertake a comparative analysis. For instance, Schreer et al. (1998) compared K-means with fuzzy c-means, SOM and artificial neural networks over both artificial and real data. Similarly, Mingoti and Lima (2006) compared SOM, fuzzy c-means, K-means and hierarchical clustering algorithms. Finally, Anard and Kumar (2022) compared different approaches. The computational results in this study can be obtained through either interaction with human knowledge (i.e., fuzzy logic, which relies on external knowledge to define membership functions and IF-THEN-ELSE rules) or a purely data-driven approach (i.e., SOMs, which aggregate information about data topology), capable of identifying clusters of similar input vectors in the absence of linear relations or external knowledge. In particular, this contribution aims to utilise a methodology that assigns fortresses to a given reuse scenario (SOMs) in conjunction with a technique that determines the degree of membership to all scenarios (FES). This is achieved by incorporating expert opinion to ascertain the potential for joint or independent utilisation.

4. CASE STUDY

A total of fifteen fortresses lie in Venice, originally built as fortified posts and strongholds according to the seventeenth-century fortresses system inspired by Vauban (Città di Venezia, 2021) (Table 1). These assets deserve consideration, given their substantial size, which ranges from approximately 12,000 m^2 to over 400,000 m^2. This diversity offers potential benefits in a city grappling with challenges related to its economy, environment and society (Zanardi, 2020).

The inventory reveals the following information: among fifteen assets, seven now accommodate new functions, with five featuring multifunctional activities and two incorporating specific and limited functions, while the remaining eight fortresses remain abandoned. Of the fifteen assets, fourteen are classified as cultural heritage, but only six are in good condition. The ownership is distributed among various entities, including the Region (one asset), the State (five assets), and the City Council (nine assets), although the latter holds rights to the State with the concession of the fortresses of Bazzera and Ca' Romano-Barbarigo. The local General Town Plan lacks specifics regarding the new use of abandoned sites, which are typically associated with generic requirements of reuse programmes that have yet to be integrated into the planning tool, as evidenced by the case of Sant'Andrea.

Table 1. Data and qualitative information on Venice's fortresses.

	Data								
Fortress	**Plot Size (m^2)**	**Époque of building / underuse-abandonment / disposal / reuse**	**Cultural Heritage (Y/N)**	**Degree of preservation (G/M/D)**	**Owner / concession**	**Current use**	**Future use**	**Reuse plan**	**Temporary use / visits**
Bazzera	37,372	1910 / 1997 / 1997 / –	Y	G	State / City Council	Cultural events by local associations	/	1996 recovery of the Mestre entrenched camp	Yes/Yes
Ca' Roman-Barbarigo	63,596	1832–1842 / 1997 / 2007 / –	Y	D	State / City Council	Abandoned	Tourist accommodation (on sale)	2011 Compensation Mose system	No/Yes
Carpenedo	308,825	1890–1892 / 1997 / – / –	Y	G	City Council	Multiuse (educational-museum, culture and social)	/	1996 recovery of the Mestre entrenched camp	Yes/Yes
Cosenz	52,892	1911 / 1997 / 1997 / –	N	M	Veneto Region	Partially reused in leisure, cultural, welfare, and social functions	Multiuse (restaurant and cultural, leisure, and tourist activities)	– 1996 recovery of the Mestre entrenched camp – 2018 federalism state property	No/No
Gazzera	262,101	1883–1887 / 1997 / 1997 / from 2019	Y	G	City Council	Multiuse	/	1996 recovery of the Mestre entrenched camp	Yes/Yes

(*Continued*)

Table 1. Continued.

Fortress	Data								
	Plot Size (m^2)	Époque of building / underuse-abandonment / disposal / reuse	Cultural Heritage (Y/N)	Degree of preservation (G/M/D)	Owner / concession	Current use	Future use	Reuse plan	Temporary use / visits
Malamocco	116,775	1830–1850/ 1976 / 1997 / –	Y	G	City Council	Abandoned	Housing, accommodation, wellness	2012 public-private real estate development	No/No
Manin	41,192	1816–1814 / 1997 1997 / –	Y	M	City Council	Abandoned/ on sale	Information center on lagoon environment	1996 recovery of the Mestre entrenched camp	No/No
Marghera	480,000	1806–1814 / 1996 / 2009 / from 1997	Y	G	City Council	Multiuse	/	Various	Yes/Yes
Mezzacapo	87,165	1910 / 1997 / 2003 / from 2003	Y	M	City Council	Multiuse	/	1996 recovery of the Mestre entrenched camp	Yes/Yes
Pepe	183,026	1909 / 1997 / 2002 / –	Y	M	City Council	Abandoned	Leisure and sports activities	1996 recovery of the Mestre entrenched camp – 2022 Tender City of Venice for enhancement proposals	No/No

Rossarol	449,368	1907 / 1997 / 2004 / from 2013	Y	M	City Council / non-profit organisation	Social and rural activities	Social rehabilitation projects, local food production	1996 recovery of the Mestre entrenched camp	No/No
San Pietro in Volta	21,374	1808–1813 / 1997 / 1997 / –	Y	M	State	Abandoned	Tourist accommodation	2019 *Cammini e percorsi*	No/No
Sant'Andrea	47,725	Sixteenth century / 1997 / 1997 / –	Y	G	State (MoD)	Abandoned	Private development	2016 enhancement programme tied to federalism state property	No/No
Santo Stefano	12,837	1859–1864 / 1997 / 1997 / –	Y	M	State	Abandoned (partially used as a car repair shop)	/	No	No/No
Tron	337,066	1887–1890 / 1997 / 1997 / –	Y	M	City Council	Abandoned	Multiuse	– 1996 recovery of the Mestre entrenched camp – 2022 Tender City of Venice for enhancement proposals	Yes/Yes

Source: Elaboration by the authors (2025).

Figure 2. An open-air leisure activity during summer 2022 at Marghera fortress.

Figure 3. A concert with a light shows in Marghera fortress.

Since 1996, the Venice City Council has launched various reuse plans, yielding scattered initiatives rather than a cohesive reuse direction, as depicted in Table 1. Notwithstanding this, a number of successful reuses have emerged, marked by the engagement of stakeholders in management plans and multifunctional reuse decisions, including the fortresses of Carpenedo, Cosenz, Gazzera, Marghera and Mezzacapo (Zanlorenzi, 2012). The case of Marghera fortress stands out as an exemplary instance, as evidenced by its transformation into a multifunctional cultural and tourist attraction, as well as a centre for social gatherings and events. Here, the Venice City Council has progressively allocated its buildings to diverse functions related to the cultural, artistic and tourist sectors (responding to Attractiveness and Dissemination models) and to activities of social aggregation (Territorial model), thus adopting a clear multifunctional reuse approach based on an integrated urban planning scheme (see Figures 2 and 3).

The collection of these successful experiences, unified by the common element of being the focus of multifunctional adaptive reuse strategies, prompts the exploration and development of tools to assess the fortified heritage's inclination toward diversified reuse scenarios.

5. EMPIRICAL ANALYSIS

From an operational perspective, this analysis introduces a framework that requires two key inputs: (i) the initial reference variables of the cultural heritage collection under consideration and (ii) expert opinions on three specific criteria, both of which will be detailed in Section 5.1. The framework utilises two sub-routines to implement the aforementioned methods: FES, based on fuzzy logic (Section 5.2) and SOMs (Section 5.3). The outputs from these methods are integrated into the main framework, representing the results of the experiments conducted (discussed in Section 5.4). What is relevant is the flexibility and generalisability of the framework adopted because it enables the incorporation of any method deemed suitable for addressing the identified problem, provided that the input-output format is maintained.

5.1. Data

The data utilised in this study were gathered through the collaboration of two expert groups, employing the methodology exposed in Section 3.1. With regard to the selection of variables, the initial group of experts (GE1) enabled the identification of a list of pertinent structural and functional characteristics that are crucial for analysing the technical-functional feasibility of fortresses reuse. Furthermore, the GE1 conducted a technical evaluation of these characteristics, utilising information extrapolated from documentary research, literature reviews, archival work at the State Archives of Venice and interviews with urban planning councillors from the Veneto Region and the Venice City Council.

A series of key aspects were given particular consideration in the evaluation of each fortified property, including the following: plot size, number of buildings and volume; period of construction; period underuse and/or abandonment, decommissioning and redevelopment into new functions; the presence of listed buildings; the degree of conservation in open and built spaces; current use; ownership (MoD, State Property, Veneto Region and City Council); and inclusion in European Union-funded projects. These characteristics are embedded in the first set of data, which is composed of numerical attributes that describe the different features, which have been evaluated by GE1.

The involvement of the second group of experts (GE2) was instrumental in determining the relative importance of each characteristic identified and evaluated by GE1 with respect to the Attractiveness, Dissemination and Territorial reuse scenarios. This information was collected through interviews using questionnaires administered via the computer-assisted web interviewing (CAWI) method. The questionnaire, following an introduction to the objectives of the interview, presented a list of characteristics of the fortresses, with the experts invited to evaluate the importance of each characteristic in achieving each reuse scenario. The list was divided into three sections, with evaluations on a scale from 0 (min) to 5 (max). A total of forty experts were contacted for interviews. The experts comprised academic staff from local universities (with ten experts from each of Ca' Foscari University of Venice and Iuav University of Venice), authorities of Venice (with ten experts from the City Council, Region and Province), and city residents affiliated with local associations. In accordance with the European privacy legislation, the General Data Protection Regulation (GDPR), the personal information of the interviewees was maintained in a confidential state.[5] In summary, this latest data set represents the opinion of GE2's experts on the direction and magnitude of the impact of the variables identified by GE1 on the three reuse scenarios. These scenarios will be used by the fuzzy logic approach to create IF-THEN-ELSE rules.

5.2. Fuzzy expert system

The fuzzy expert system (FES) is predicated on the utilisation of fuzzy logic, wherein membership functions are employed to assign values to variables or assertions, thereby signifying their degree of belonging to a fuzzy set. This process is designated as 'fuzzification'. It then applies inference rules to generate precise ('crisp') values, which assist users in decision-making and optimisation, a process known as 'defuzzification'.

In implementing an FES, during the fuzzification, numeric inputs are converted into linguistic variables, and a less specific linguistic characterisation is defined, aligning with Zadeh's principles (1975). Specifically, crisp inputs are associated to the degree to which these inputs belong to each of the appropriate fuzzy sets. The information collected in the survey conducted with GE2 served to outline a first reordering of the contribution of the characteristics of each fortified asset to the realisation of each reuse scenario (see Table 2).

The term-set associated with each input variable has been defined as {Low, Medium, High}. Inputs have been normalised with the Min-Max formula, and triangular-shaped *membership functions* have been used for the inputs (see Figure 4).

Then, during the 'inference' phase, the *Fuzzy Inference Process* applies inference rules to generate a fuzzy output, by using IF-ELSE statements and linguistic rules (i.e., logic operators), in two phases. The first is the 'implication', which defines the fuzzy consequence for each rule, and the second is 'aggregation', which combines all output fuzzy sets of all rules into a single fuzzy set. The process needed to associate a fuzzy concept to a fuzzy condition via the Generalised Modus Ponens rule (see Blot et al., 2016). For all the implemented rules, the linguistic rule AND (corresponding to the logic operator 'min') has been applied amongst inputs. Then, the smallest input value has been selected, and the fuzzy consequent value evaluated. The term-set associated with the output variable (corresponding to the suitability of reuse for the scenario taken into account) has been defined as {Very Low, Low, Acceptable, High, Very High}. Triangular (in the middle) and trapezoidal (at the edges) membership functions have been used for the output, as suggested by Andria et al. (2020). The linguistic rule OR (corresponding to the 'max' operator) has been used to aggregate all the output membership functions.

Finally, defuzzification converts the fuzzy output into a crisp value that best corresponds to it. In this study, the Centre-of-Sums defuzzification method (Hellendoorn & Thomas, 1993), followed by MAX-MIN normalisation, was used to generate a numerical aggregate. This aggregate indicates the suitability of a fortress for reuse in a given scenario, reflecting the 'intermediate values' produced by the fuzzy approach (Rizzo et al., 2022). Essentially, the fuzzy approach assigns a score to each fortress across three reuse scenarios, aiming to algorithmically capture the concept of reuse. By converting quantitative data into qualitative insights, it integrates expert opinions to compute a final numeric value that represents the suitability of a particular reuse scenario for each fortress. However, the complexity of this method can compromise the

Table 2. Impact of the observed variables on the three hypotheses of reuse, according to the experts' replies.

Variable name	Attraction	Dissemination	Territorial
Availability of commercial services	Very High	High	Acceptable
Availability of cultural services	Very High	Very High	Acceptable
Availability of leisure services	Very High	Acceptable	Acceptable
Availability of services of general interest	Very High	High	High
Distance to airport	Very High	High	Acceptable
Distance to motorway gate	Very High	Very High	Acceptable
Distance to railway station	Very High	Acceptable	Acceptable
Integration of the asset site	High	High	Acceptable
Proximity to cultural attractive point of interest	Very High	Very High	Acceptable
Proximity to logistic platform	High	High	Acceptable
Proximity to tourist recreational point of interest	Very High	Acceptable	High
Proximity to potential source of pollution	Very Low	Acceptable	Very Low
Proximity of traffic pollution	Very Low	Acceptable	Very Low
Proximity of traffic noise	Very Low	Acceptable	Very Low
Size of the site	High	Very High	High
Availability of clean water	Very High	Very High	Very High
Availability of sewage	Very High	Very High	Very High
Availability of electricity	Very High	Very High	Acceptable
Availability of other energy	Very High	Very High	Acceptable
Availability of heating system	Very High	Very High	Acceptable
Number of floors	Very High	Acceptable	Acceptable
State of site's conservation	High	Very High	High
Possibility to increase building's volume	High	Very High	Acceptable
Space availability for parking	Very High	Very High	Very High
Existence of legal constrains	Very High	Very High	Acceptable
Public visibility	Very High	Very High	Very High
Presence of frescos	Very High	Acceptable	High
Presence of architectural values	Very High	High	Very High
Availability of feasibility study	Very High	High	Acceptable
Availability of cultural development	Very High	Very High	Very High
Availability of cartographic supports	High	Very High	Acceptable

Note: For each variable, all replies have been collected, and for each couple of [variable, reuse], the magnitude (belonging to Very Low, Low, Acceptable, High, Very High, corresponding to the maximum number of replies has been selected).
Source: Elaboration by the authors (2025).

interpretability of results, underscoring the necessity to compare it with a more straightforward, data-driven approach that functions independently of external expert knowledge.

5.3. Self-organising maps

Self-organising maps (SOMs) were developed by Kohonen (1990) and are used to project extensive sets of data in a two-dimensional representation, thereby enabling the user to assess the relationships between the data and their features. The present contribution employs a single layer of neurons distributed in a two-dimensional grid, to which the unlabelled inputs are presented. As an output, SOMs will visualise the nonlinear relations amongst the multidimensional input via a map of neurons.

The algorithm defines a randomly initialised vector of weights associated with each neuron, the components of which correspond to the components of the input vector. The

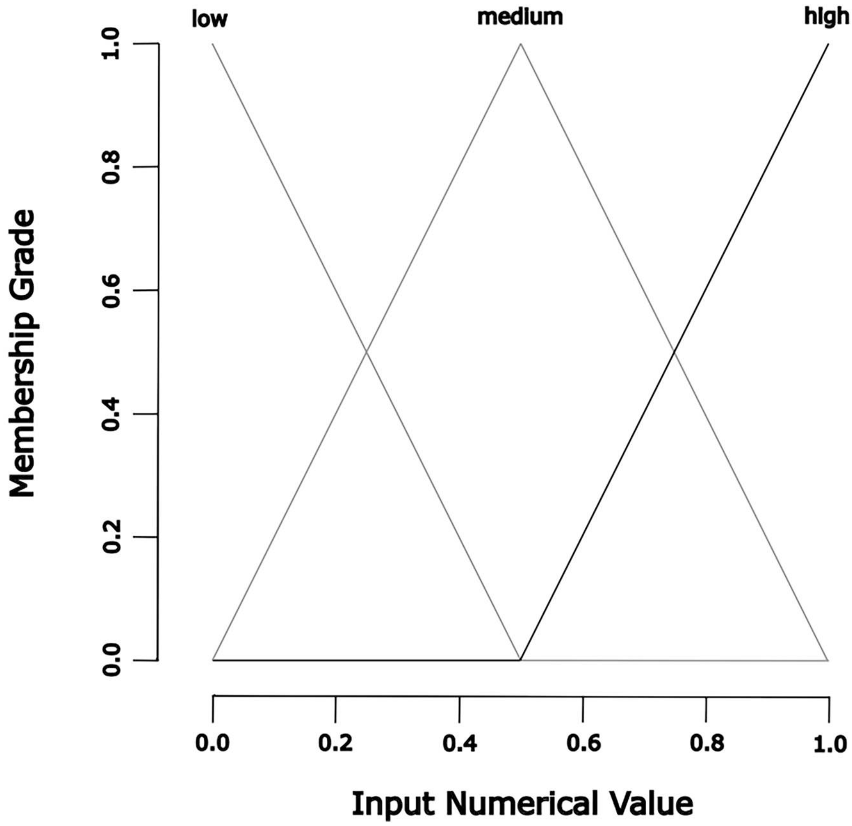

Figure 4. Membership function corresponding to the input variables.

training is performed via iteratively presenting the input, and via identifying the best matching unit, i.e., the neuron whose Euclidean distance between its weight vector and the input vector is minimised; then the weights of neighbouring neurons are updated according to a neighbourhood function.

After the training, the resulting map of neurons must be analysed to identify clusters composed of neurons featuring small pairwise distances between them. The reuse scenario information is embedded through a vector that defines four different scenarios, corresponding to Attractiveness, Dissemination, Territorial and a hypothetical 'Unclassified', which should contain the fortresses whose reuse is deemed difficult to identify. It is important to note that the scenarios have not been provided to SOMs during the training, but rather after the resulting final map has been determined, in order to identify how the inputs have been organised.

5.4. Results

This section outlines and compares results obtained from the FES and from the SOMs model. Table 3 reports the main statistics of the results obtained (i.e., Attractiveness, Dissemination and Territorial) obtained with the FES. It is important to note that different rules have been applied to the three scenarios, and therefore they are not mutually exclusive.

Table 4 reports the values obtained by the FES for the three scenarios, which are also visually represented in Figure 5. Furthermore, it shows the average and standard deviation of the three

Table 3. The values, mean and standard deviation of the attraction, dissemination and territorial scenarios.

	Attraction	Dissemination	Territorial
Maximum	0.5278	0.60213	0.66296
Minimum	0.33047	0.39297	0.41852
Mean	0.46329	0.4934	0.54284
StdDev	0.044	0.03814	0.04981

Source: Elaboration by the authors (2024).

Table 4. Values indicating the suitability of reusing the fortifications listed in 'Denomination fortress' for the three scenarios (attraction, dissemination and territorial) as determined by the fuzzy approach (FES).

Denomination fortress	Attraction	Dissemination	Territorial	Avg. of the three scenarios	Std. Dev. of the three scenarios
Bazzera	0.47289	0.52438	0.57467	0.5240	0.0508
Caroman-Barbarigo	0.45167	0.50119	0.57125	0.5080	0.0600
Carpededo	0.49875	0.50119	0.58352	0.5278	0.0482
Cosenz	0.49733	0.49994	0.57467	0.5239	0.0439
Gazzera	0.49875	0.47827	0.52542	0.5008	0.0236
Malamocco	0.47422	0.53226	0.58255	0.5296	0.0542
Manin	0.49733	0.50127	0.58255	0.5270	0.0481
Marghera	0.52167	0.54702	0.6003	0.5563	0.0401
Mezzacapo	0.51428	0.51894	0.57739	0.5368	0.0351
Pepe	0.47458	0.45411	0.52417	0.4842	0.0360
Rossarol	0.50521	0.52305	0.59778	0.5420	0.0491
San Pietro in Volta	0.47289	0.50127	0.55156	0.5085	0.0398
Sant'Andrea	0.49733	0.49994	0.57467	0.5239	0.0439
Stefano	0.45167	0.45536	0.5025	0.4698	0.0283
Tron	0.5204	0.5229	0.5761	0.5398	0.0314
Avg. over fortresses	0.4899	0.5040	0.5666		
Std. Dev. over fortresses	0.0224	0.0261	0.0282		

Source: Elaboration by the authors (2024).

scenarios over each single fortress (i.e., the last two columns), and the average and standard deviation of each single scenario over all fortresses (i.e., the last two rows).

With regard to the FES, it is noteworthy that for all fortresses, the values assigned to the three different paradigms are closely aligned within the interval [0.3–0.6]. The most significant disparity among the paradigms is lower than 0.1 in 42 out of 45 pairwise, and it falls within the range [0.1–0.2] in the remaining three cases. None of the three paradigms demonstrate a significant predominance over the others, despite the Territorial paradigm being the most prevalent. The estimations of the fuzzy logic prove that reuses based on multiple functions are equally viable and more effective in dealing with the tendency of assigning one function to the assets. Indeed, the sites located in the extreme Venetian hinterland (i.e., the areas with the greatest residential, tourist and logistical intensity) demonstrate the greatest reuse capacity in all scenarios.

In contrast to the allocation of each scenario to a given real number for each fortress, the SOM approach assigns every single fortress to a given re-use scenario. In the experiment,

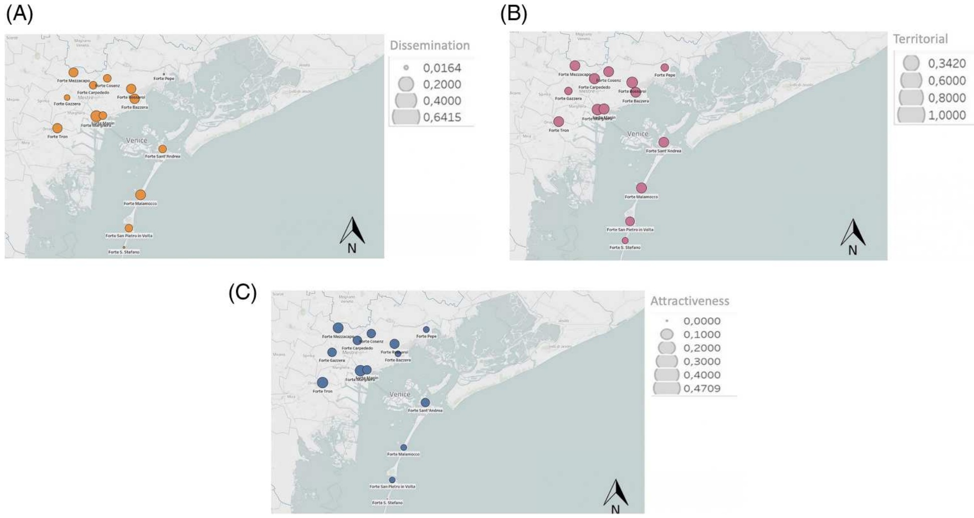

Figure 5. Suitability for reuse of fortifications for the three scenarios (top photo: dissemination, (A); central photo: territorial, (B); bottom photo: attractiveness, (C): visualisation of the fuzzy approach (FES) results on the municipality of Venice.

four different clusters have been delineated, given that SOM does not assign labels. These clusters should correspond to Attractiveness, Dissemination and Territorial, in addition to an extra class designated for fortresses that should remain Unclassified. The outcomes of both approaches are compared in Table 5, which shows the contingency table illustrating the number of fortresses in each of the clusters generated by the two tools. In this table, cell (i, j) denotes the common elements (i.e., the common fortresses) between clusters i (identified by the fuzzy approach) and j (as identified by SOM).

It is noteworthy that the two fortresses, Pepe and Santo Stefano, classified under the Unclassified group by the SOM, correspond to the fortresses with the lowest standard deviation in the three scenarios identified by the fuzzy approach, as indicated in Table 3. Additionally, the results of the SOM approach frequently exhibit the highest values detected by the fuzzy approach to the Attractiveness and Diffusion scenarios. The consistent identification of the Territorial scenario by both tools not only confirms the greater cardinality of the Territorial scenario but also suggests that the SOM and FES are comparable and capable of overcoming the biases induced by the experts' responses.

A final analysis is presented through the 'weight planes' obtained by the SOM approach, as depicted in Figure 7. These planes illustrate the weights connecting each input to the SOM

Table 5. Common elements (fortresses) pairwise differences between clusters identified via FES and SOM.

Denomination fortress	F-Attraction	F-Dissemination	F-Territorial
SOM1	0	0	8
SOM2	0	0	3
SOM3	0	0	2
SOM4	0	0	2

Notes: F-i indicates fortressed obtained by the fuzzy approach (FES) whose reuse belongs to scenario *i*; SOMj represent the jth clusters obtained by SOM ($j = \{1..4\}$).
Source: Elaboration by the authors (2024).

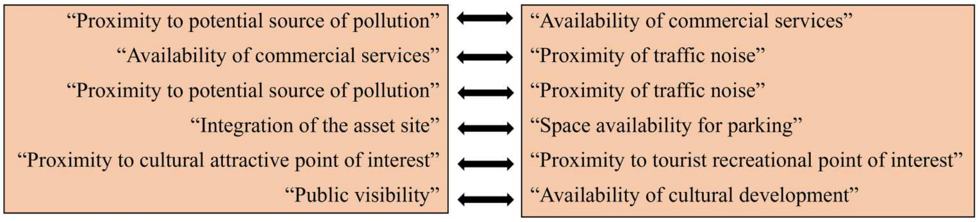

Figure 6. Stronger correlation according to the weight planes SOM analysis.

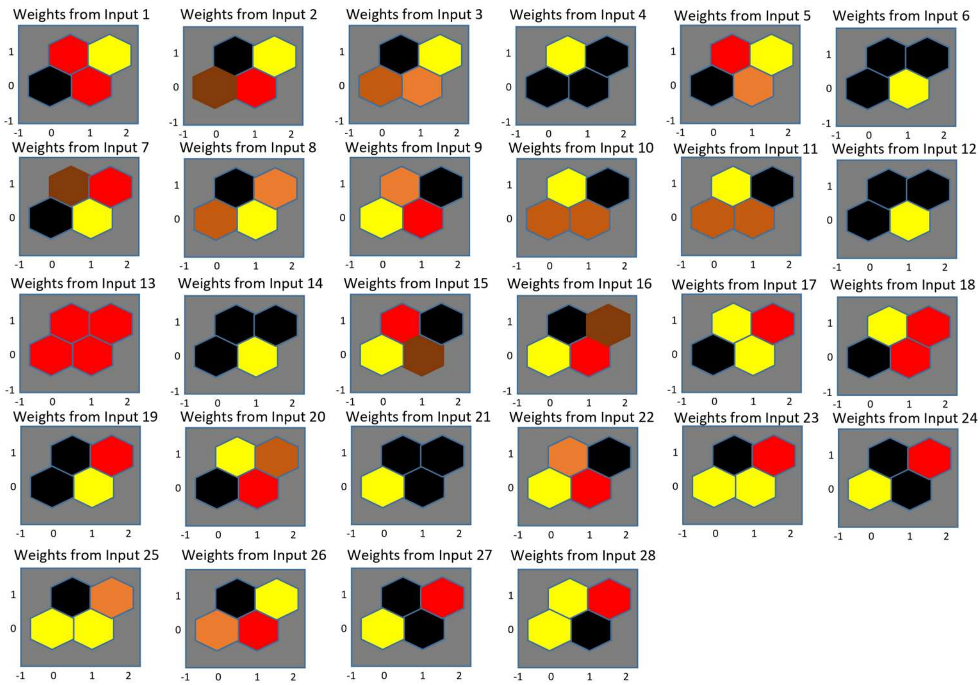

Figure 7. Pairs of input variables showing similar input weights according to the weight planes SOM analysis.

neurons, with darker colours indicating higher weights. In essence, if the connection pattern of two input variables is similar, there is a high likelihood that the two inputs have the same (or at least a highly correlated) effect on the output. Accordingly, a strong correlation is observed among the pairs of variables shown in Figure 6 (see Figure 7 for the comprehensive overview of the weight plane).

A comparison of the information from this analysis with the data contained in Table 2 is of interest. The latter shows the impact of all variables on the three-reuse scenario, as assessed by GE2. Not surprisingly, three out of six of the aforementioned pairs consist of variables that have a significant effect on the three scenarios ('Integration of the asset site' and 'Space availability for parking'; 'Proximity to cultural attractive point of interest' and 'Proximity to tourist recreational point of interest'; 'Public visibility' and 'Availability of cultural development'). However, evidence suggest that there are also pairs of variables showing inverse relations over one scenario and a lower effect on the remaining two ('Proximity to potential source of pollution' and 'Availability of commercial services'; 'Availability of commercial services' and 'Proximity of traffic noise'). Furthermore, a pair of variables show low impacts over two scenarios ('Proximity to potential source of pollution' and 'Proximity of traffic noise'). These findings confirm that SOMs are apt to generalise information about data, without resorting to external expert knowledge.

6. DISCUSSION AND CONCLUSIONS

As posited by frontrunner scholars (Bagaeen & Clark, 2016; Camerin & Gastaldi, 2018), the intricate process of converting former military sites into sustainable civilian spaces has been the subject of scant attention in cross-cultural analyses. These analyses have predominantly concentrated on identifying best practices and formulating guidelines with the potential for international transferability (Camerin & Córdoba Hernández, 2024). The absence of exhaustive research engenders challenges for communities, governments, developers and planners grappling with incompletely tested land use configurations, partnership structures and financing strategies. Despite the numerous experiments and efforts made in recent years in this research field, a paucity of understanding of the full scope of challenges and effective solutions in facilitating these transformations remains.

The case study of the fortresses of Venice demonstrates significant tangible assets and considerable potential for conservative reuse. However, the protracted period of abandonment has been a fundamental factor in the current degradation of the built environment and open spaces. Moreover, the reuse of these assets is characterised by a persistent tension between the short-term budgetary imperatives of public entities divesting military land and the long-term requirements of the local community.

The results of the FES analysis indicate a favourable feasibility for reuse projects based on the Territorial scenario. This finding aligns with the current state of fortress reuse in Venice, which is primarily focused on the fortress's conservation. However, the findings also suggest that the Territorial reuse scenario could also be combined with those of Attractiveness and Dissemination, given the limited gap that emerges among them in accordance with the applied fuzzy logic model. The absence of a pronounced predominance of a singular scenario is noteworthy, underscoring the manifold prospects for the repurposing of these assets and the viability of a multifaceted approach to fortress reuse. This outcome assumes particular significance when considering that the inventory of the fifteen sites analysed in this study, which shows that only fortresses that have undergone multifunctional adaptations are associated with successful management and reuse status.

The findings, when considered collectively, emphasise the feasibility and fundamental role of diversified reuse strategies for fortresses in achieving positive outcomes for the adaptive redevelopment of this specific cultural heritage. The fortresses that embraced the Territorial scenario and implemented diversification strategies (such as the Carpenedo, Gazzera and Marghera fortresses) effectively capitalised on their potential associated with the Attractiveness and Diffusion scenarios. This underscores how the integration of these three scenarios can lead to the successful and efficient reuse of fortresses. In contrast, singular investments geared towards a specific use, aligned with neoliberal urban policies, have experienced limited success.

The case study analysis indicates that monofunctional fortresses are not as effective in a city like Venice, where overtourism exerts a significant impact on the economic and social structure without delivering substantial benefits to local development (Baldin et al., 2024). Conversely, assets that have undergone multifunctional reuses, concurrently linked to tourism, dissemination and conservation, demonstrate superior performance in terms of routine maintenance and utilisation by residents and users. In the specific case of Venetian fortresses, this may be linked to the fact that merely conservative or tourist reuse scenarios, mostly linked to the mass tourism and cultural vocation of Venice, do not seem to activate either new development opportunities or adequate maintenance and heritage protection.

The multifunctional reuse has the potential to stimulate three key areas in the planning of a future scenario for Venice's territory that is more oriented towards the needs of citizens. Firstly, it may be possible to develop the urban tourist industry. Secondly, it may be possible to activate a process of attracting inward investment and strengthening the competitive position of industries. Finally, it may be possible to promote citizens' engagement in political and public life to influence the decision-making about the reuse of cultural heritage for people of different ages, social classes, genders, lifestyles and ethnic origins. The involvement of citizens may eventually provoke unexpected outputs, including enhanced quality of life and the revitalisation of 'dead space' and 'dead time'.

The historic centre and hinterland of Venice are currently facing a number of urgent socio-economic and environmental challenges, including overtourism, population decline and a deteriorated lagoon system (Camatti et al., 2024; Cristiano & Gonella, 2020). In order to address these issues, it is essential that policies are adopted which focus on the prudent use of the region's heterogeneous local territory resources. By focusing on the peculiarities that mark the local fortresses, public authorities can not only develop locally preferred solutions but also design innovative and effective strategies in support of sustainability. The implementation of multifunctional plans for their reuse is instrumental in achieving these objectives. The methodology outlined in this paper provides a valuable framework for the generation of prototype solutions, which can be used to analyse alternative reuse scenarios for cultural heritage on an international scale. Consequently, the application of the methodology can trigger the identification of reuse strategies that contribute to the effective regeneration of the territory and its cultural heritage, yielding economic, environmental and socio-cultural benefits.

As illustrated in Figure 8, while this study applies the proposed analytical framework to fortified heritage, it can be extended to encompass other forms of cultural heritage as well. Its systematic approach serves as a versatile tool for identifying viable reuse scenarios for tangible cultural assets more broadly. Indeed, the framework remains grounded in three key pillars: firstly, the intrinsic structural characteristics of the cultural asset and its territorial context, secondly, insights and assessments from external experts, and, thirdly, pre-established reuse scenarios that guide the analysis. The structural data and geographical context considered in this framework can be adapted to heritage assets beyond the Venetian fortresses, extending its applicability to a wide range of cultural assets in diverse regions. The introduction of additional

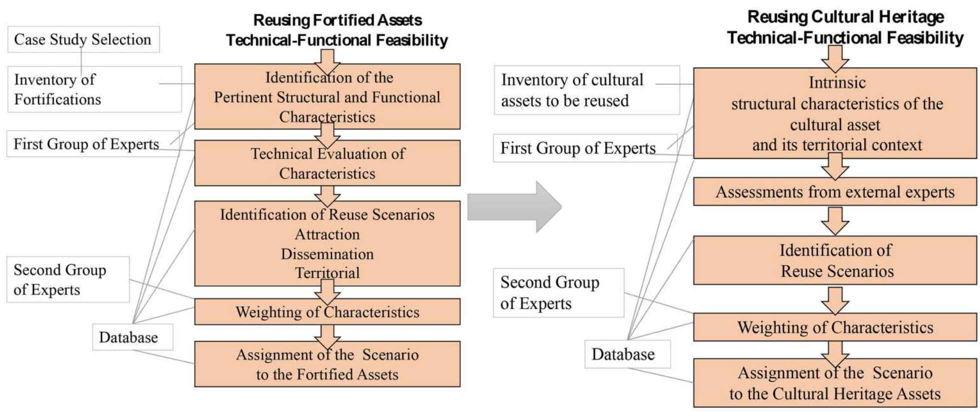

Figure 8. Analytical framework: from the case study to generalisation for cultural heritage reuse in predefined scenarios.

variables, as outlined in Table 2, could be considered to account for the unique characteristics and requirements of different cultural contexts. Moreover, the number and type of reuse scenarios can be either expanded or narrowed, depending on the specific historical, cultural and social needs of the region being studied.

Regardless of the variables or scenarios involved, the incorporation of external expert evaluations remains a fundamental and integral part of the decision-making process. These expert assessments are crucial in ensuring that the reuse strategies are context-sensitive, informed and aligned with the cultural and historical significance of the assets under consideration. The methodology, therefore, offers a flexible yet robust approach for fostering sustainable reuse practices across diverse cultural heritage contexts.

The two models employed in this study, FES and SOMs, demonstrate a convergence in identifying the 'Territorial' scenario as the most suitable reuse approach for the majority of fortresses, while simultaneously underscoring significant opportunities for the implementation of the alternative scenarios. The integration of these two models can yield an innovative framework for the analysis of cultural heritage reuse scenarios, encompassing a data-driven approach complemented by external knowledge contributed by experts.

While FES demonstrates a strong capacity to incorporate varying expert opinions it is difficult to assess its robustness definitively, as each analysis is dependent on the current state of external knowledge. In contrast, SOM does not necessitate external knowledge and is completely robust regarding different data characteristics. In addition, the FES analysis also provides a ranking of the three scenarios, providing valuable insights for policymakers within an MCDM framework. While SOM can be employed for assignment purposes without the need for external knowledge, it does not inherently convey this information.

Despite their different mechanisms, both models converge on the same optimal reuse solutions, thereby corroborating findings from previous studies, such as those by di Tollo et al. (2012), which highlighted the benefits of combining these methods. Both models are computationally efficient, requiring minimal time and hardware resources. Nevertheless, the fuzzy approach, which is contingent on the selection of experts, the collection of their assessments, and the processing of that information, is more time-consuming and susceptible to noisy and redundant data. This has the potential to impede the automation of the process. Therefore, when designing a reuse detection procedure, it is crucial to weigh the time required against the constraints and deadlines set by policymakers.

In scenarios where time is a limiting factor, SOMs may be more suitable, as they provide faster, automated results. Conversely, for exercises with looser time constraints and a need for more detailed interpretability of results, a combination of FES and SOMs would be more appropriate.

Future research should concentrate on assessing the scalability of this methodology across different geographic and cultural contexts. The proposed approach relies on data that can be retrieved and quantified for various geographic assets, regardless of their specific typology (e.g., military or non-military). The analysis should also be expanded to incorporate additional data sets, thereby enabling experts to identify new variables that may influence reuse scenarios. While the FES analysis would need to be redefined to incorporate these new variables, no modifications would be required for the SOM model, demonstrating its flexibility.

As emphasised in the Methodology section, algorithms for reuse analysis can be categorised into two distinct groups: (i) methods that rely on external expert knowledge and (ii) purely data-driven approaches. Further studies should conduct a comprehensive comparison of these two classes of methods. Each method involves parameter settings that influence outcomes, so a sensitivity analysis of these parameters is essential. The development and comparison of procedures for tuning and controlling parameters is essential, with consideration given to both pre-run tuning (where parameters are set before execution) and dynamic control (where parameters are adjusted during execution), in addition to their combination. To support this effort, alternative techniques such as bi-clustering and random forests could be explored.

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CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Roles played by contributors, Nicola Camatti (NC), Giacomo Di Tollo (GDT), Francesco Gastaldi (FG) and Federico Camerin (FC) to research outputs: Conceptualisation: NC and GDT; Data curation: NC and GDT; Formal Analysis: NC and GDT; Funding acquisition: NC and GDT; Investigation: FG and FC; Methodology: NC and GDT; Project administration: FG and FC; Resources: FG and FC; Software: NC and GDT; Supervision: FG and FC; Validation: FG and FC; Visualisation: FG and FC; Writing – original draft: NC, GDT and FC; Writing – review and editing: NC, GDT and FC.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, C. F., upon reasonable request.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

NOTES

1 https://forte-cultura.net/index.php/Ansicht/getData/103
2 https://www.fortresortbeemster.nl/en/
3 https://forte-cultura.net/index.php/Ansicht/getData/101
4 https://forte-cultura.net//Ansicht/getData/44
5 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L:2016:119:TOC

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