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Construction Solutions, Cost and Thermal Behavior of Efficiently Designed Above-Ground Wine-Aging Facilities

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Abstract: The wine industry requires a considerable amount of energy, with an important fraction corresponding to the cooling and ventilation of above-ground aging warehouses. The large investments made in aging facilities can compromise the viability and competitiveness of wineries if their design is not optimized. The objective of this study was to provide guidance for the efficient design of new above-ground warehouses. To this end, multiple construction solutions (structure, envelopes, levels of integration, etc.) were characterized, and their costs and the resulting interior environments were analyzed. The results offer a comprehensive view of potential construction solutions and benchmark price ranges for viable and profitable designs. With a total cost of 300 EUR/m^2, an average damping of 98% per day can be achieved. Increasing the costs does not imply better effectiveness. A double enclosure with internal insulation—with or without an air chamber—can achieve excellent results. Greater integration as a result of several enclosures being in contact with other rooms and/or the terrain allows for a high effectiveness to be achieved without air conditioning. Perimeter glazing and ventilation holes can reduce the effectiveness of the construction, resulting in greater instability and a lower damping capacity.

Keywords: wine; aging; above-ground warehouse; construction; cost; damping

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1. Introduction

The wine industry is one of the industries that is the most affected by climate change [1], but on the other hand, it contributes significantly to global warming [2], and it can be considered an energy-intensive industry, as it produces approximately 0.3% of the annual global greenhouse gas emissions [3].

Some of these emissions are due to energy consumption in wineries, which is mainly associated with the process used in aging rooms to cool and ventilate warehouses [4]. This is because wine requires very strict environmental conditions for its aging and maturation, which must be maintained throughout many months of the year. Indeed, although an optimal interval has not been established, various authors have pointed out that if the temperature rises above 18–20 °C, the quality of the wine decreases [5–7] and evaporation losses occur [8]. It is also accepted that temperatures below 4–5 °C slow down the aging of wine [9]. Frequent temperature changes are also harmful and may compromise the wine's longevity [7,10]. In addition, ventilation must be promoted to avoid the appearance of harmful mold [11,12]. In wineries with natural ventilation systems, critical factors emerge, such as mold growth or wine evapotranspiration, and ventilation has been proven to be poorly designed, as it is either insufficient or excessive [13]. Therefore, the use of climate control equipment is common in aging rooms that do not passively meet the described requirements. HVAC is the most in-demand equipment for reducing temperatures [14].

The challenge faced by many wineries is the high cost of climate control to ensure optimal conditions for wine aging. This issue has been exacerbated in recent years due to the increase in energy prices. For instance, the energy bill of a Spanish winery doubled in just one year from 2021 to 2022 [15]. The prospects of energy price instability and high costs have the potential to impact the competitiveness and viability of numerous wineries.

Under these circumstances, various strategies for reducing the energy bills of wineries have been examined. Thus, for example, in a Greek winery, replacing the air-to-liquid cooling unit with PV panels demonstrated 54.7% energy savings and a payback period of 3.6 years [16]. The integration of a Portuguese winery into an energy community with collective photovoltaic self-consumption in a small city promoted a higher penetration of photovoltaic capacity (up to 23%) and achieved a modest reduction in the overall cost of electricity (up to 8%) [17]. The amount of biogas generated in a wine production plant was sufficient to supply all of the necessary energy used by a Chilean winery [18].

Long before the implementation of renewable energies, a sector of the wine industry embraced nearly zero-energy buildings, which prevented the need to invest in climate control during wine aging. Over the last two decades, numerous studies have analyzed the effectiveness of constructions with high thermal inertia, such as underground, sheltered, and basement designs. In Italy, a partially underground solution produced a reduction in the cooling energy demand of 75% in comparison with an above-ground solution, reaching 100% with an underground solution [19]. Ideal temperatures can be reached inside an underground cellar without air-conditioning expenses in several locations across the world by adjusting the depth according to the ground properties and exterior conditions [20]. Basement constructions have an acceptable capacity for reducing outdoor variations and can be an inexpensive solution for indoor climate control. On the contrary, above-ground constructions without air-conditioning systems or ground thermal mass present lower capacities for reducing outdoor variations, as they have less control over climate conditions [21].

Despite the energy advantages offered by constructions with high thermal inertia, the increased initial investment required, potential issues due to high relative humidity, and other operational aspects (the use of forklifts, presence of pillars, increased difficulty in handling barrels, etc.) continue to make above-ground wineries the more common solution. For unconditioned warehouses in Italy, several variations in architectural elements and retrofit interventions have been studied through simulations with the aim of enhancing buildings' responses and minimizing energy consumption. The results showed that, in general, roof and wall interventions were more effective than orientation and solar shading, and the combination of more strategies allowed for improved results to be achieved [22,23]. Mazarrón et al. [24] characterized the indoor environment of a typical non-climate-controlled winery in Spain and analyzed its thermal response in different locations of the world through simulations, concluding that the hygrothermal conditions could go well beyond acceptable limits, especially during the summer months. High temperatures can lead to the rapid aging of wine, reducing its quality and increasing wine losses. In these types of warehouses, natural lighting can play a key role due to its low thermal inertia and its influence on the variance in temperature and humidity [25].

Faced with the future scenario of climate change, scientific studies aimed at reducing energy requirements in aging rooms have gained significance. A recent study conducted on nearly zero-energy-consumption buildings used for the aging of sherry wine, known as cathedral wineries, demonstrated that climate change could render these above-ground buildings less effective, causing them to require climate control [26].

With regard to the impact of the design on winery costs, the precedents are scarce. Accorsi et al. [27] delved into the design of warehouse buildings aimed at reducing their cycle time, total expenses, and carbon footprint. The results highlighted that the total cost and the carbon footprint functions led to similar warehouse configurations that were distinguished by a compact vertical structure. Ramos-Sanz [28] conducted an analysis of the cost-effectiveness of passive strategies that were applied to the envelope of a winery situated in Argentina. It was concluded that the incorporation of thermal insulation in the walls and adiabatic reinforcement in the roof was effective to the extent that the minimum thickness of the insulation was greater than or equal to 0.12 m, achieving savings of 54% in the total cooling demand. Gómez-Villarino et al. [29] demonstrated that in constructions with high thermal inertia, there were notable differences in cost, damping effectiveness, and the resulting hygrothermal environment depending on the type of building. The correlation between performance and construction costs showed large differences in cost per degree of damping achieved. The average cost was 0.7 ± 0.2 EUR/m^2 for buried warehouses, 1.1 ± 0.5 EUR/m^2 for basement warehouses, and 2.5 ± 0.5 EUR/m^2 in the case of underground constructions. In the case of above-ground warehouses, Beni et al. [19] quantified the cost of one in Italy and compared it with other high-thermal-inertia designs by estimating the thermal behavior through simulations. Aside from reducing the energy demand, the underground building solutions that were analyzed involved significantly higher construction costs, with increases ranging from 12% to 27% in comparison with those of above-ground constructions. This is one of the reasons why cheaper and less efficient buildings have been preferred for wine production in recent decades.

There is no record of previous studies breaking down the costs of multiple construction solutions used in above-ground warehouses where quality wine is produced and correlating them with the actual thermal response. Given that this typology represents the most common design of wine-aging facilities, having a benchmark to aid in the efficient design of new aging rooms and their subsequent management is essential. Hence, this study examined multiple construction solutions (facades, roofs, and floors) used in above-ground warehouses where quality wine is produced and characterized their cost, thermal behavior, and effectiveness. The main objective was to provide guidance for the efficient design of new above-ground warehouses and the improvement of existing ones.

2. Materials and Methods

Multiple factors influence the design of above-ground wineries. In this study, the most significant ones were analyzed, which were the cost, insulation, and thermal inertia of construction solutions used in the envelopes (roof, enclosures, and floor), the structure, the level of integration (exposure to the exterior), and the presence of ventilation and lighting openings.

To achieve the proposed objective, it was necessary to identify a large number of wineries and select several in which quality wine was produced. Subsequently, a characterization of the construction of the aging rooms and general aspects of the wineries was carried out, and the current construction cost was quantified to enable comparison within a consistent framework. A monitoring system was installed in each aging room to characterize the indoor and outdoor environments throughout the year for a subsequent analysis of the internal stability and the effectiveness of mitigating external variations.

2.1. Analyzed Warehouses

For the selection of the analyzed warehouses, many of the wineries present in Spain were identified. After making contact with 3863 wineries via telephone and/or email, 389 wineries agreed to conduct a subsequent survey on their general characteristics. A final selection of 10 above-ground wineries was made by taking the construction solution, the winery's interest in collaboration, and the availability of a construction project on which to base the study into account.

The selected wineries produced high-quality wines. They were scattered among referential producing regions, such as La Ribera del Duero, Rioja, and Madrid (Figure 1). In particular, the monitored warehouses belonged to the Alvarez Alfaro, Castillejo de Robledo, Emina, Hermanos Pascual Miguel, Legarís, Mauro, Moradas de San Martín, Murua, Resalte de Peñafiel, Ribera, and Valdelosfrailes wineries.

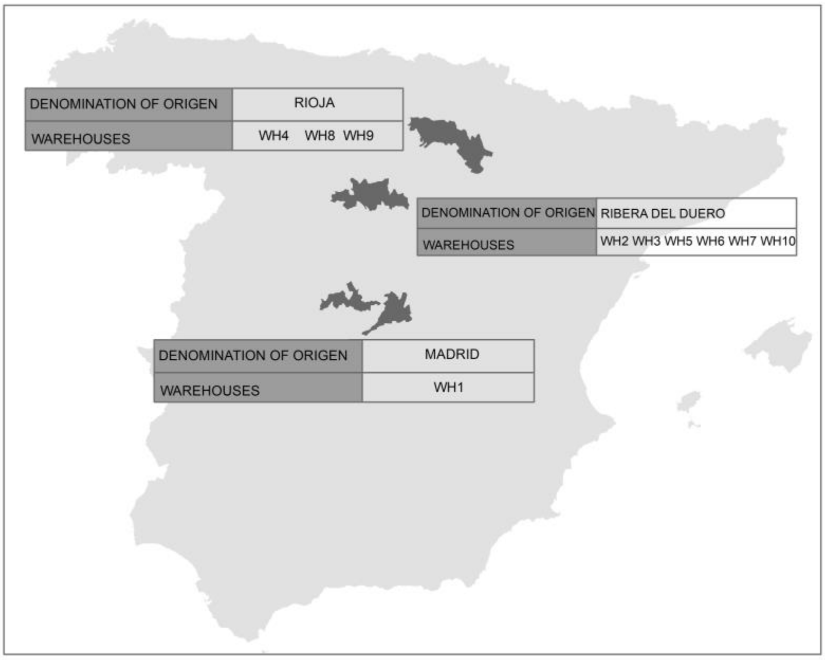

Figure 1. Locations of the analyzed warehouses.

2.2. Characterization of Construction

The characterization of the construction included both constructive aspects (materials, properties, thicknesses, construction systems, etc.) and their costs based on information provided by the wineries (projects, work certifications, etc.), as well as information collected through non-destructive methods during visits.

For each warehouse, a file with general data on the winery and specific data on the aging room was generated (Figure 2). The aging room was understood as a space that was partially or totally separated from the rest of the buildings in the winery in which barrels were permanently housed to age the wine. The file was completed with elevation plans, designs, and structures; together with the construction details, these data allowed for the construction costs of the wine warehouses to be updated.

The detailed information in the files included the following: identification of the winery, location, description, microclimate, photos of the aging room, exterior photos, construction characteristics, facilities, budget, structure, plant, elevation, section, construction details, plan with sensor locations, and observations. The following details of the construction characteristics were included as follows: foundation, floor, structure, pavement, roof, enclosure, carpentry, and construction details.

In order to compare the construction costs of all of the warehouses within the same frame of reference, all of the original budgets for the same year were calculated. Together with the original plans, the construction details allowed us to obtain the budget items and measurements necessary to calculate an updated budget of the construction costs of each aging room (Figure 3). For this purpose, the CYPE 2023 budget program and the Presto 17.03 software, which are reference software for budgets, measurements, and cost control for buildings, were used, as they allowed for the costs of the different work units and the budgets to be systematically updated in a standardized way.

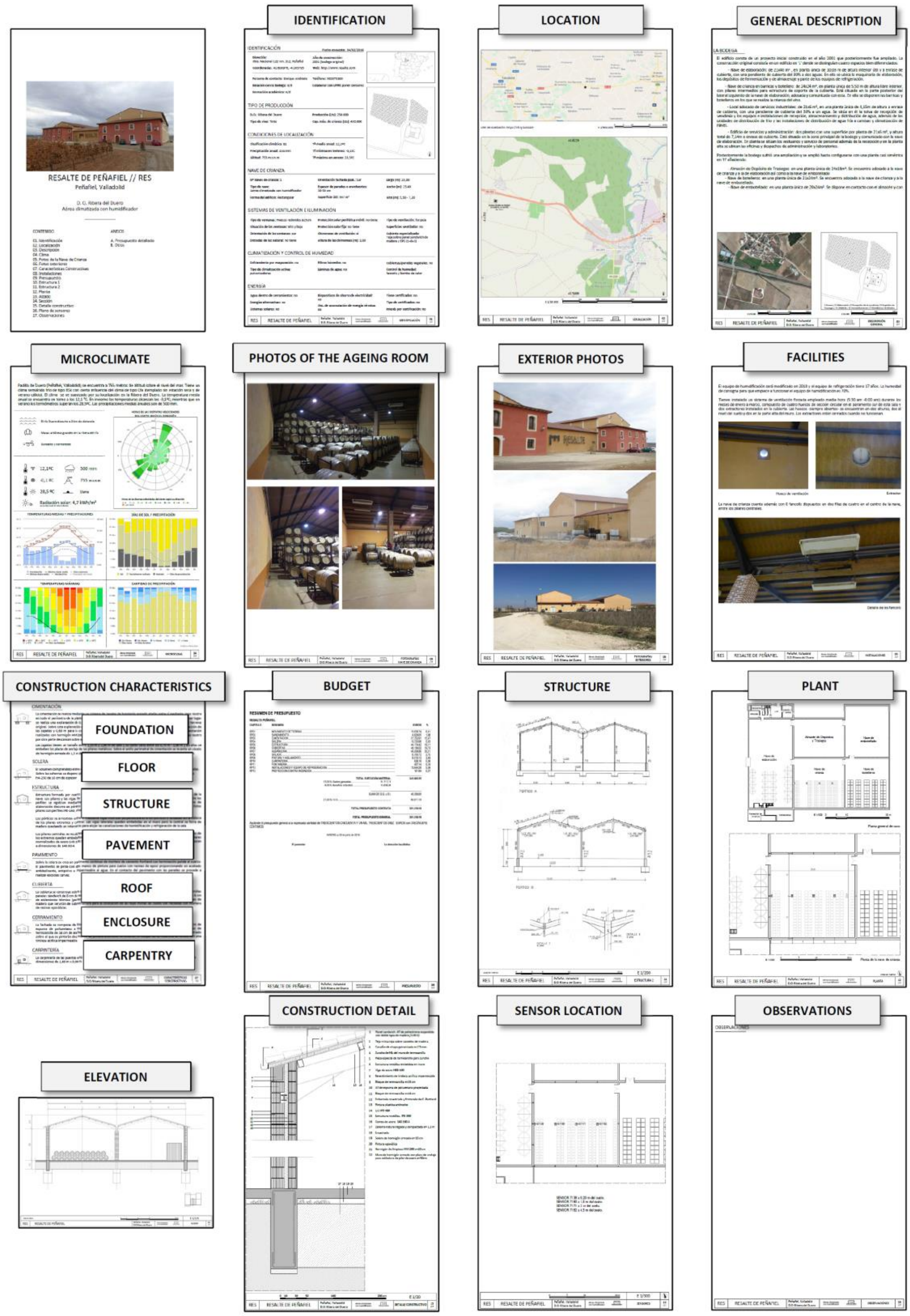

Figure 2. Example of the different pages that made up a construction characterization file.

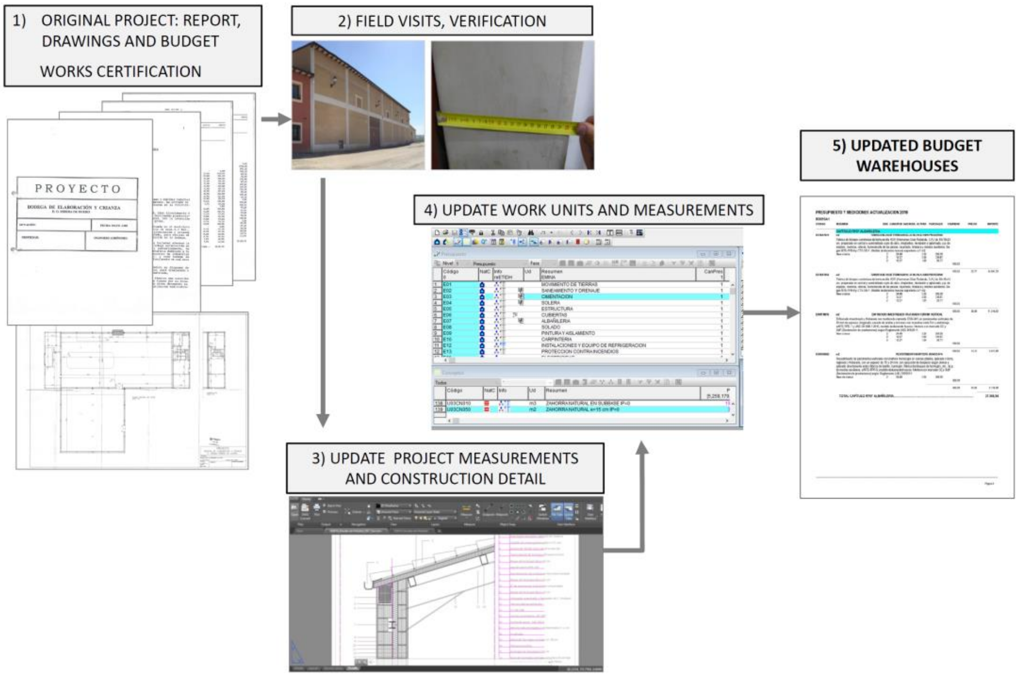

Figure 3. Example of the process of updating the budget of a warehouse.

2.3. Thermal Behavior and Effectiveness

The monitoring was carried out using Hobo Pro v2 (Hobo®) temperature recorders to monitor the outdoor environment (accuracy of ± 0.18 °C at 25 °C and resolution 0.02 °C) and OM-92 (Omega) recorders for indoor temperature monitoring (accuracy of ±0.3 °C from 5 to 60 °C and resolution of 0.01 °C). The long experience of the research team in the monitoring of warehouses (more than a decade) has shown that the interior environment of warehouses is very uniform on the horizontal plane, with marked differences in the vertical plane, which has a strong stratification in the summer months [30]. Therefore, in each warehouse, sensors were installed at various heights at a central point of the barrel room, and the average temperature to which the barrels were subjected was calculated. The monitoring period was 1 year, and a measurement interval of 15 min was used.

The analyzed wineries were spread throughout Spain and, thus, were subject to different external conditions. Therefore, the effectiveness of the warehouses was quantified according to their ability to dampen outside temperature variations, which was equivalent to previous work in warehouses [20,21,24,29]. Specifically, thermal damping was calculated as a percentage of the external variation:

$$\text{Damping}(\%) = \frac{\Delta\text{T exterior} - \Delta\text{T interior}}{\Delta\text{T exterior}} \quad (1)$$

Considering that most above-ground warehouses where quality wines are made have powerful air-conditioning equipment that controls the increase in temperature in the summer months (and, in some cases, at other times of the year), the annual damping is not reliable for the determination of the effectiveness of a construction solution. Therefore, daily damping was used while considering periods without air conditioning.

The thermal stability of the warehouses was also analyzed, and it was calculated as the difference between the average temperatures of two consecutive weeks. This indicator provided an insight into the rate at which the temperature changed indoors.

3. Results and Discussion

Firstly, the construction solutions used in the facades, partitions, roofs, floors, and structural elements of the selected wineries (producers of quality wines) were characterized, and their impacts on the total costs of the aging facilities were determined. The level of integration of the warehouse within the winery and its exposure to the external environment were also assessed. The aim was to provide the sector with benchmark values for designing new wineries and improving existing ones.

Subsequently, a characterization of the resulting indoor environment was conducted by quantifying the damping and stability achieved to provide the optimal conditions required for wine aging. These data can serve as key performance indicators (KPIs) for wineries in this sector to gauge their situation and room for improvement.

Finally, through an analysis of periods without climate control, relevant conclusions were drawn regarding the effectiveness of the construction solutions, the level of integration, and other pertinent parameters. The insights extracted should be taken into consideration in the design of new efficient above-ground wineries.

3.1. Construction Solutions

3.1.1. Envelopes

The envelope in any construction is an intermediary between the outside climate and the environment within the structure. The analysis of the envelopes of the aging rooms made it possible to identify the various solutions used in the analyzed warehouses (Figure 4), and their theoretical construction costs (per m^2 of enclosure surface) were quantified. Aesthetic elements that were not relevant to the model and affected the final cost (stone finishes, special paintings, etc.) were eliminated.

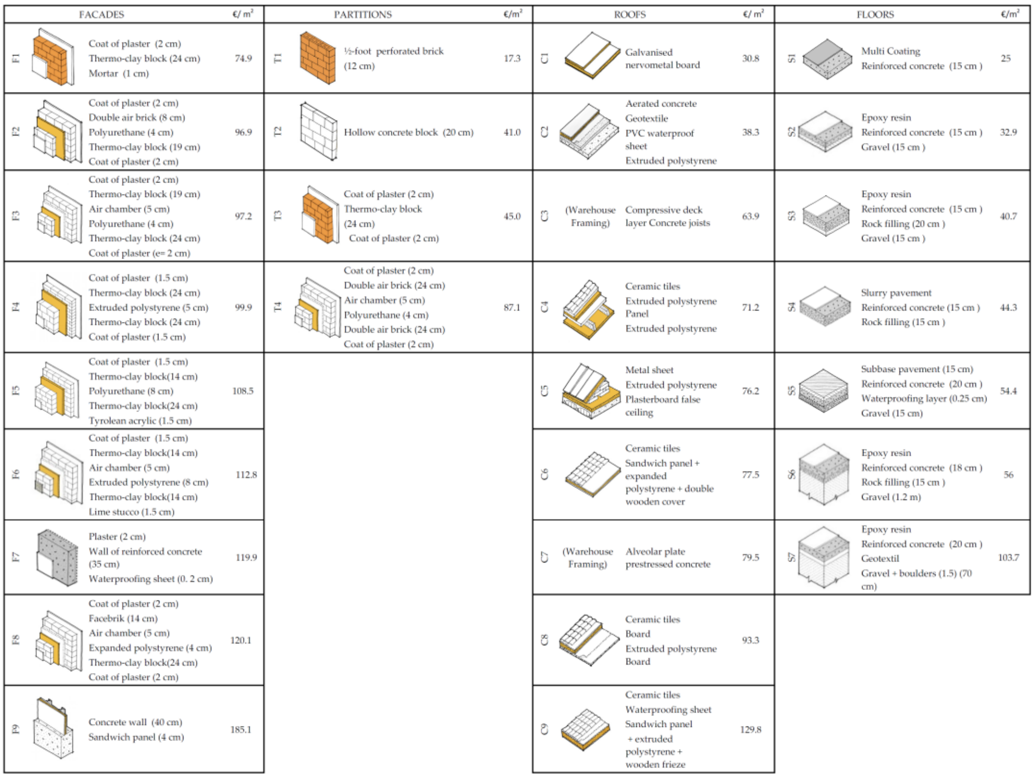

Figure 4. Standard construction solutions that made up the envelopes of the aging rooms.

These construction solutions were grouped according to common features in the facades, floors, and roofs. Thus, five models of facades were identified (Table 1), and their costs varied between 75 EUR/m^2 for the simplest enclosures composed of a rendered prefabricated element (27 cm) and 185 EUR/m^2 for solutions with a greater cost that included concrete walls and sandwich panels with a thickness of 44 cm. However, the most commonly used enclosure, which had a width that ranged between 35 and 50 cm, consisted of two layers (exterior and interior) of brick or thermo-clay and an insulating element inside that could also include a chamber of air, with an average cost of 106 EUR/m^2.

Table 1. Identified facades grouped according to their common characteristics.

Facade Model	Facades	Description	Thickness cm	Price EUR/m^2
I	F_1	Prefabricated and rendered board	27	75
II	F_2 F_4 F_5	Sandwich wall composed of two thermo-clay or brick walls with a thermal insulator inside and exterior cladding	35–56	97–110
III	F_3 F_6 F_8	Sandwich wall composed of two thermo-clay or brick walls with a thermal insulator and air chamber inside and exterior cladding	44–56	97–120
IV	F_7	Reinforced concrete wall	37	120
V	F_9	Concrete wall and sandwich panel	44	185

The floors were arranged directly on the ground without insulation, and they were grouped into six models (Table 2). The minimum thickness was 15 cm in the simplest solution, which consisted of a massive concrete slab plus a basic cement pavement, which had a cost of 25 EUR/m^2. The maximum thickness reached 90 cm for a concrete floor on a level mounted on compacted stuffing and extended bolting, which had a cost of 104 EUR/m^2. The most common solution was gravel, reinforced concrete, and pavement, with a cost that varied depending on the pavement used—from basic cement pavement to an epoxy resin.

Table 2. Identified floors grouped according to their common characteristics.

Model Floor	Floors	Description	Thickness cm	Price €/m^2
I	S_1	Concrete + pavement	15	25
II	S_2	Gravel + concrete + pavement	30	33
III	S_4	Rock filling + concrete + pavement	30	44
IV	S_5	Gravel + waterproofing layer + concrete + pavement	35	54
V	S_3 S_6	Gravel + filling + concrete + cement—chalky sand/pavement	50	40–56
VI	S_7	Gravel and boulders + geotextile + concrete + pavement	90	104

The roofs had a greater heterogeneity (Table 3). They mostly consisted of a sandwich panel or board that incorporated some insulation and were finished with ceramic tiles. Their price had a wide range, from 31 EUR/m^2 for a very simple solution of a deck roof with insulation boards to the most expensive and complex solution formed by a wooden frieze, double insulation layer with a sandwich panel, and ceramic tiles with a cost of 130 EUR/m^2. However, most of the solutions showed an average cost of 80 EUR/m^2 and consisted of a sandwich panel or a board with insulation and were finished off with tiles.

Table 3. Identified roofs grouped according to their common characteristics.

Roof Model	Roof	Description	Price EUR/m^2
I	$C_1{\cdot}C_2{\cdot}C_4{\cdot}C_6{\cdot}C_8{\cdot}C_9$	Insulated	31–129
II	C_5	With insulation and false ceiling	76
III	$C_3{\cdot}C_7$	Warehouse framing	64–80

3.1.2. Structural Elements

In terms of structural elements, there was a huge diversity of solutions depending on the type of soil, the topography of the ground, and the type of structural solution. This was reflected in the dispersion of the costs, which ranged from 61 EUR/m^2 to 306 EUR/m^2, with an average cost of 119 EUR/m^2.

In general, the warehouses were adapted to the terrain, and the earthworks had an average cost of 16 EUR/m^2, except for cases in which important earth movements were carried out, where a maximum of 63 EUR/m^2 was reached. The impact of excavation on the building costs was defined in previous studies [29]. This impact is especially significant when an aging room is built on sloped land to take advantage of the ground to achieve better conditions with fewer influences from exterior fluctuations. In these cases, the structure requires the movement of a considerable amount of soil and the construction of a reinforced concrete retaining wall, which drives up the costs. Indeed, this is reflected in the foundations costs, which greatly vary depending on the type of soil, the location of the warehouse, and the most suitable depth. In this case, the costs varied from 10 EUR/m^2 to 168 EUR/m^2.

3.1.3. Level of Integration of the Aging Room in the Warehouse as a Whole

The range of options related to the integration of the aging room in the rest of the construction is very diverse. On one hand, independent warehouses, with all of their facades and roofs exposed to the outside, can be found; on the other hand, there are warehouses that are integrated into a set with a single exposed facade, with the rest of the facades and roofs bordering other warehouses or the land (Table 4).

Table 4. Level of integration and cost of the warehouses analyzed (E: outdoor environment, T: terrain, N: warehouse).

	Construction Cost EUR/m^2 Warehouse			Code of the Construction Solution						Envelope Contour		
	Total	Envelope	% Total Reduction	Facades		Roof		Floor		Lateral	Upper	Lower
WH1	558	249	1	II	F4+T1	I	C8	II	S2	3E/0T/1N	E	T
WH2	287	177	4	III	F6	II	C5	II	S2	3E/0T/1N	E	T
WH3	455	224	5	V	F9+T3	I	C1	II	S2	3E/0T/1N	E	T
WH4	471	268	2	I	F1	I	C9	V	S6	3E/0T/1N	E	T
WH5	440	194	3	II	F2	I	C8	V	S3	2E/0T/2N	E	T
WH6	363	212	8	II	F5	I	C6	IV	S5	1E/0T/3N	E	T
WH7	270	115	6	II	F2	I	C2	II	S2	1E/0T/3N	E	T
WH8	350	183	10	III	F8+T2	I	C4	I	S1	0.5E/0.5T/3N	E	T
WH9	771	254	6	III	F3	III	C7	VI	S7	1E/1T/2N	N	T
WH10	325	198	8	IV	F7+T4	III	C3	III	S4	1E/2T/1N	N	T

An increase in the level of integration resulted in a decrease in the cost of the aging room, since the cost of common envelopes was divided between the two rooms. Thus, the impact on the cost of the common envelopes between the rooms that shared them implied a reduction in the cost of the aging room by 1% to 10% depending on the shared area, the unit cost of the shared elements, and the percentage represented by the envelope with respect to the total budget of the warehouse (Table 4). Another aspect that reduced the cost of the aging room being integrated was the possibility of using partitions instead of walls, as they had a lower cost of construction (Figure 4).

The structure was the part of the construction system that, together with the facades, had the greatest influence on the total cost (Figure 5). On average, the structure represented 33% of the budget, the facade represented 20%, and the roof represented 18%.

Focusing on the cost associated with the envelope, the facade usually represented the most important cost, making up, on average, 40% (22–70%) of the total cost of the envelope, while the roof represented 34% (13–56%), and the floor represented 26% (14–47%). Therefore, a reduction in the facade surface implied a significant reduction in the cost of constructing the envelope.

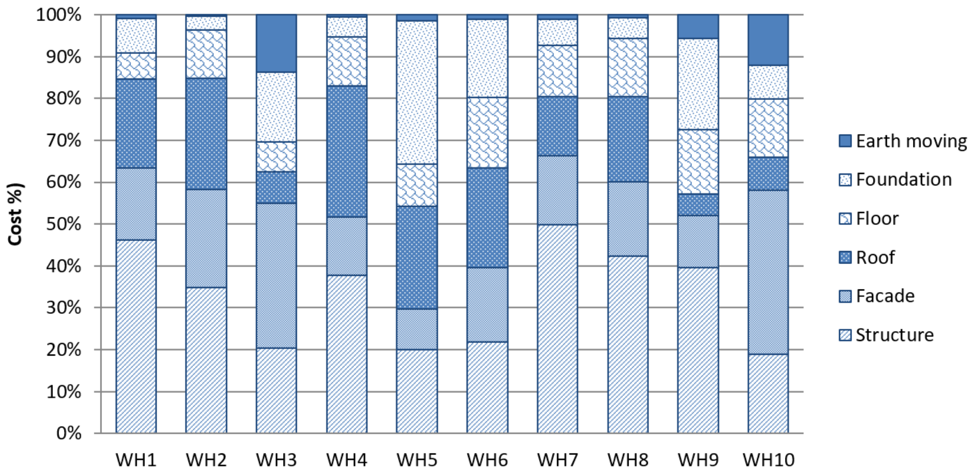

Figure 5. Percentages of costs associated with the main items in the budgets of wine cellars.

The average cost per square meter of the aging room when considering the envelope was 207.4 EUR/m^2 (115–268 EUR/m^2); the average cost for the facades was 120.6 EUR/m^2 (185–75 EUR/m^2), that for roofs was 84.5 EUR/m^2 (31–129 EUR/m^2), and that for the floor was 56.5 EUR/m^2 (25–103 EUR/m^2).

3.2. Thermal Behavior of the Warehouses

The thermal behavior of the warehouses was characterized through an analysis of the evolution of the indoor temperature throughout the year, its relationship with the external environment, the percentage of damping achieved, and the interior stability (the speed at which the temperature changed).

3.2.1. Temperature Inside the Warehouses

Every warehouse, excluding WH10, required climate control systems during the summer months to maintain the interior temperature within the limits established by oenologists. The operational period and the set target temperature varied according to each winery's specific requirements. For instance, in warehouses 2 and 6, the maximum temperature was set to 15 °C, which implied the need for climate control from July to October. On the contrary, warehouse 9 only activated its HVAC for a mere 2 months in an attempt to maintain the interior temperature at 19 °C (Figure 6), as could be observed in August and September.

In spite of that, the indoor temperatures of WH2 and WH6 remained 5 to 10 degrees lower than the outdoor temperature for most of the summertime (weeks 25 to 37). In both cases, the combination of the facades and roofs provided thermal inertia through the incorporation of an insulation with a high thickness. In the remaining warehouses, the most critical period was the summertime, as the temperature difference went over 5 °C during the three hottest summer weeks (Figure 7).

Moreover, certain warehouses, such as WH5 and WH7, also needed climate control during the winter months to maintain the minimum temperatures set by oenologists based on technical criteria or to conduct malolactic fermentation (Figure 6). Therefore, during certain weeks in winter, the indoor temperature exceeded the outdoor temperature by more than 10 °C, whereas in some warehouses, the difference was closer to 5 °C (Figure 7).

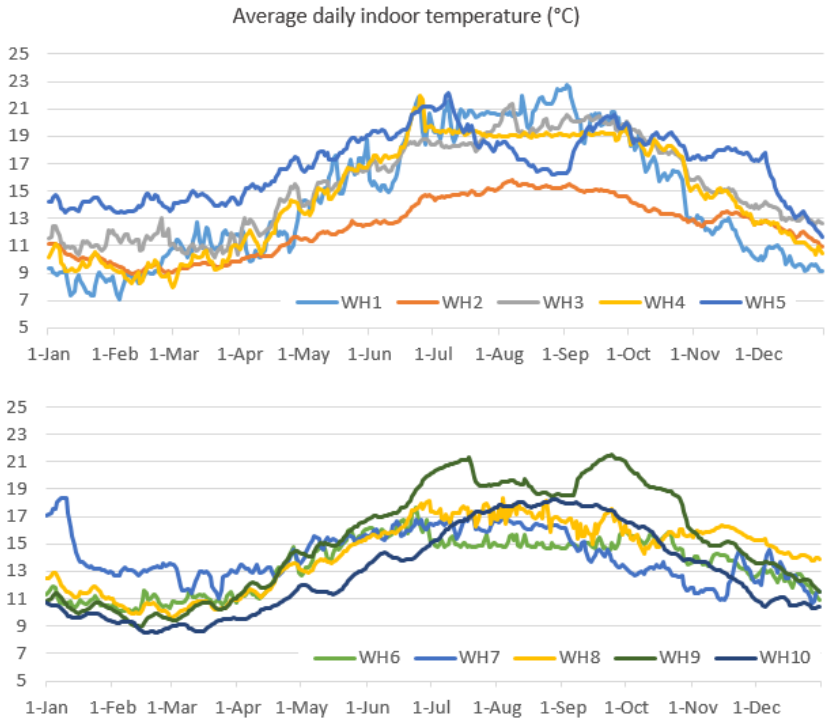

Figure 6. Average daily temperatures inside the monitored wineries.

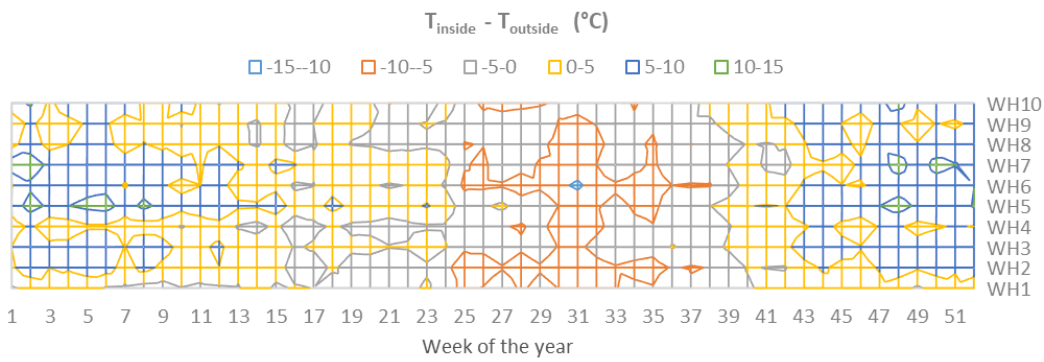

Figure 7. Average weekly temperature difference between inside and outside (°C).

3.2.2. Damping

Most of the wineries were effective in dampening the variations in the temperature of the outdoor environment, which meant that their wine was subjected to stable conditions that allowed proper aging. The annual damping values were 50% (WH1), 64% (WH4), 72% (WH3 and WH9), 76% (WH5), 77% (WH8), 79% (WH10), 80% (WH7), 81% (WH6), and 84% (WH2). The damping values that were obtained (except for that of WH1) were significantly higher than the 53% damping obtained in a previous study conducted in an above-ground warehouse without air conditioning [24]. The excessive ventilation of WH1 resulted in an effectiveness in dampening external variations that was equivalent to that of an unconditioned cellar. The range of values obtained in the remaining above-ground warehouses aligned closely with those of basement warehouses (between 67% and 85%) [21,29], which was attributed to the implementation of climate control. In optimal scenarios, parity was achieved with buried warehouses (83–88%) [21,29] and certain subterranean ones (78–92%) [20,21,29], even when they did not reach the maximum values.

When the annual damping was analyzed, only the case of WH10 led to unequivocal conclusions regarding the effectiveness of the construction solutions, as the values in the rest of the warehouses were greatly influenced by climate control in the summer period. In this case, a huge amount of thermal inertia in all of the construction systems justified the performance, with a clear delay in the daily temperature curve, which was characteristic of these types of buildings. Therefore, it was essential to analyze the daily damping achieved during periods without climate control.

Every warehouse except WH1 showed a mean daily damping that was greater than 90%, reaching 99% in some cases; that is, the difference between the maximum and minimum temperatures recorded each day represented between 1% and 10% of the measurements outside. Specifically, the values were 79 ± 12% (WH1), 98 ± 1% (WH2), 91 ± 7% (WH3), 92 ± 3% (WH4), 98 ± 2% (WH5), 93 ± 4% (WH6), 91 ± 5% (WH7), 96 ± 5% (WH8), 98 ± 3% (WH9), and 99 ± 1% (WH10). In most of the warehouses, the capacity for dampening fluctuations in the outdoor temperature remained relatively constant throughout the year both with and without air conditioning (Figure 8). Only warehouse 1 exhibited variations that were significantly above the average. However, this lack of efficiency was due to the fact that it was frequently opened, which seemed to cause excessive ventilation. Therefore, daily damping stands as a potential indicator of the efficiency of warehouse construction solutions, contingent upon it not being compromised by excessive ventilation.

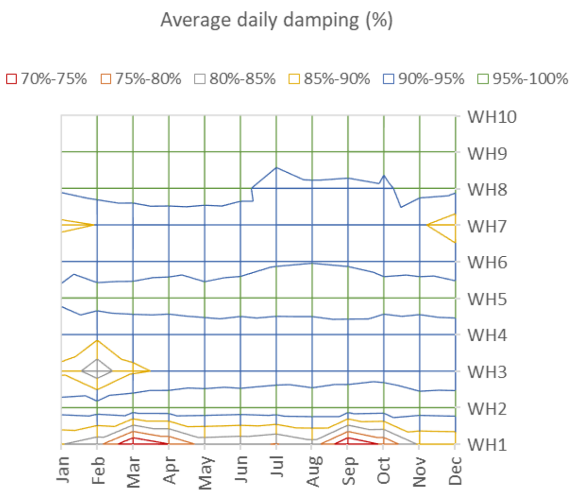

Figure 8. Daily average damping in each of the analyzed warehouses.

3.2.3. Stability

Similarly to the damping case, most of the analyzed warehouses maintained good levels of thermal stability, providing constant thermal conditions for the wine. The rate at which the mean temperature changed was low, averaging below 1 °C per week for a significant portion of the year (87% of weeks), with 56% of weeks experiencing variations below 0.5 °C (Figure 9).

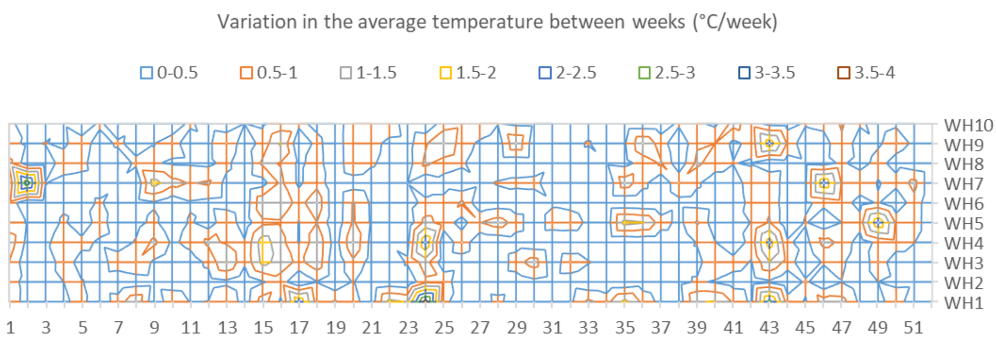

Figure 9. Weekly variations in average temperature when considering absolute values (°C/week).

The highest stability was observed in warehouses WH2 (annual average of 0.3 ± 0.2 °C/week), WH6 (0.4 ± 0.4 °C), WH08 (0.5 ± 0.3 °C), and WH10 (0.4 ± 0.3 °C). In those cases, the combination of the thermal inertia in the construction systems and the appropriate position and thickness of the thermal insulation was the key to this performance. Slightly higher values were observed in warehouses WH3 (0.6 ± 0.5 °C/week), WH4 (0.6 ± 0.6 °C), WH5 (0.6 ± 0.5 °C), WH7 (0.6 ± 0.6 °C), and WH9 (0.6 ± 0.5 °C). In most warehouses, there were no significant differences in stability between periods with and without climate control, yielding similar annual averages when the summer months were excluded. Therefore, stability stands as a potential indicator of the efficiency of warehouse construction solutions.

The least favorable performance was, once again, evident in WH1, where faster fluctuations in temperature (0.8 ± 0.7 °C/week) were caused by excessive ventilation. At certain times of the year, its weekly average temperature could experience variations of almost 4 °C (Figure 9). The flow rates of the climate control equipment and/or exterior ventilation might have compromised the potential stability of the warehouse.

3.3. Effectiveness of the Construction Solutions

The diverse comfort intervals set by oenologists and the consequent activation of climate control systems complicated the quantification of the effectiveness of the adopted construction solutions. Nevertheless, significant insights into the design and subsequent management can be derived by analyzing the data at daily and monthly intervals, with a particular emphasis on periods without climate control.

Within the envelope of a warehouse, the roof is one of the most important elements because of its exposure to the outdoor environment. In this case, the incorporation of thermal inertia is recommended to damp thermal fluctuations and stabilize indoor conditions, and it should be combined with thermal insulation to avoid excessive thermal fluxes of energy. All of the analyzed warehouses that had daily damping values greater than 90% had a slab floor (a massive indoor element) and included a thermal insulating layer with or without an air chamber. The incorporation of a space cushion could reduce the thermal increase and contribute to temperature damping. In addition, it was also clear when the space located in an aging warehouse was a living one due to the limitation of energy transfers towards the outside.

Regarding the facades, the warehouses that had a double layer of thermo-clay or hollow brick with a high thickness and a minimum of 4 cm of insulation (WH8, WH9, WH13, WH14, etc.) achieved high damping values. In these cases, as mentioned above, the combination of thermal inertia and thermal insulation was fundamental for the optimization of the performance by reducing gains and losses of energy while stabilizing the indoor conditions.

Equivalently, the warehouses with the highest levels of integration and with facades that were in contact with the ground (WH8, WH9, WH10) also achieved high levels of damping of oscillations in the external environment, with daily damping values that were greater than 95%, which was in line with previous research on high-thermal-inertia designs [29]. Warehouse WH10 was the only one that did not need air-conditioning equipment to achieve high damping in the summer months (99% daily damping).

In general, the combination of thermal inertia and thermal insulation achieved with thermo-clay walls, thermal insulation, and different specialized layers with insulation in the roof allowed for good levels of damping to be achieved. This was the case of WH4 (92% daily damping), which had the lowest facade cost of those analyzed (75 EUR/m^2), where the influence of the construction of the roof was clear.

There did not seem to be a clear relationship between the cost of the envelope of the aging room and the daily damping that it achieved (R^2 below 0.2 in a linear regression) or between the cost and the stability indicator (R^2 below 0.2 in a linear regression), since both depended on multiple parameters. Increasing the costs does not imply better damping; on the contrary, it was sometimes associated with relatively low damping values. From a total cost of 268 EUR/m^2 and 115 EUR/m^2 for the envelope, daily damping values of 98% could be achieved.

4. Conclusions

A comparison among a great diversity of construction solutions used in above-ground warehouses for the aging of quality wines was performed. It provided benchmark values for the cost of enclosures and structural elements to help in the design and expense control for new wineries.

- The average cost per square meter obtained for the envelope of an aging room was 207.4 EUR/m^2 (115–268 EUR/m^2); the average cost obtained for the facades was 120.6 EUR/m^2 (185–75 EUR/m^2), that of roofs was 84.5 EUR/m^2 (31–129 EUR/m^2), and that of the floor was 56.5 EUR/m^2 (25–103 EUR/m^2).
- The total cost increased unevenly depending on the solutions used in the structure and other construction elements, with the total price with respect to the area (square meters) of the warehouse ranging between 270 EUR/m^2 and 771 EUR/m^2.
- The level of integration of the warehouse in the entirety of the construction was associated with a lower cost of the envelope, with the added advantage that the surface exposed to the outside environment was reduced.

The characterization of the construction was complemented by an analysis of the thermal behavior and effectiveness of the solutions that were employed. This comprehensive approach allowed for the extraction of benchmark values and key factors to consider in the design of new wineries.

- The external temperature buffering achieved in most above-ground wineries was equivalent to that of basement, buried, and some underground wineries. However, this required climate control for 2 to 4 months per year. The lower initial investment was offset by the energy costs needed throughout its lifespan.
- Most of the analyzed constructions exhibited a good capacity for buffering against daily external fluctuations (average buffering between 91 and 99%), remaining relatively consistent throughout the year. Similarly to the damping case, most of the analyzed warehouses maintained good levels of thermal stability (average variations close to 0.5 °C per week), providing suitable aging conditions.
- Perimeter glazing and infiltration through ventilation can reduce the effectiveness of the construction. The above-ground wineries appeared to be highly sensitive to excessive ventilation, making this a crucial factor in both their design and subsequent management.
- A high level of integration achieved by having several enclosures in contact with other rooms (including the roof) and/or the ground minimized the exposure to outdoor conditions and allowed high damping to be achieved without air-conditioning equipment. This type of design can be a good alternative to basement or underground wineries while maintaining the advantages of above-ground facilities.
- A larger investment does not imply the better performance of a warehouse in terms of damping or the stability of the temperature.
- A lack of thermal insulation on the floor allows for the use of the thermal inertia of the ground and the stabilization of the temperature (as an energy sink). However, perimetral insulation can reduce the exchange of the envelope and should be taken into consideration.
- In all cases, a combination of thermal inertia and a suitable insulation thickness (which could be as low as 4 cm) was the most suitable solution for reducing the energy transfer through the envelope while preserving the indoor hygrothermal conditions. The roof had a notable effect on the thermal stability of the buildings. In facades, a double layer (thermo-clay or hollow brick blocks, not midfoot) with internal insulation—with or without an air chamber—achieved good damping results.

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