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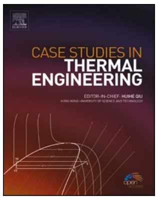

Optimal capacity for sustainable refrigerated storage buildings

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A R T I C L E I N F O

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A B S T R A C T

Widespread construction of cold storage buildings is important to ensure sustainability of the agricultural industry and reduce food loss. However, the number of cold storage buildings in most developing countries is insufficient because of financial difficulties. Currently, the most critical factor for encouraging investors to finance such projects is the payback period. In this study, the power consumption and profitability of cold storage buildings were investigated based on their capacities using data from selected cold stores in Turkey. The optimal storage capacity was calculated by simulation, and the relationship between the payback period and the capacity of cold stores was analysed using the obtained results. It was found that the amount of power consumed per unit volume for stores with capacities from 100 to 2100 t of apples was 63.8% while that from 2100 to 10000 t was 33.3%. Additionally, the optimal cold storage capacity was determined to be 3500 t with a two-year payback period.

1. Introduction

Project design and project management of cold storage buildings are important aspects of sustainability. The proper use of resources is essential to sustain economic growth and reduce environmental impacts. Cold storage is a key factor for worldwide food safety, which also affects the environment. According to the International Institute of Refrigeration, 475 million tonnes of perishable foods were spoiled in 2013 in developed and developing countries because of lack of refrigeration. This lost food could have been saved by using cold storage and could have theoretically fed 950 million people in that year [1]. Consequently, the Rome Declaration was signed by 76 countries in November 2019 to support the development of a sustainable cold chain.

Cold storage projects, which are gradually increasing in number, must be properly designed as part of a comprehensive energy efficiency solution. One of the important parameters to ensure efficient design is the optimal storage capacity, which depends on many factors. These factors should be examined in all stages of the life cycle a cold storage building, i.e. from construction to operation.

Recent studies on cold stores have focused on energy savings because cold storage buildings consume considerable amounts of energy. The energy consumed by cold storage has increased from 4 to 250 kWh/m^3 annually [2], and this energy must be managed efficiently. To achieve this, cold storage design should consider both user requirements and efficiency. Studies have shown that in cold storage facilities, 60–70% of the electrical energy is consumed by the refrigeration system [2]. Therefore, energy savings can be achieved by improving the refrigeration system. Various studies have been conducted on this topic, including the use of phase change materials in cold stores, which has been reported to generate a 5–10% savings in energy [3–5]. In addition, research on solar cooling applications [6,7] and advanced control management strategies [8] have also been performed with the goal of energy savings.

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Moreover, it is possible to obtain an average of 25% in energy savings by improving room insulation alone [9]. Furthermore, improvements in the system performance can be achieved by using alternative refrigerants [10] and selection of suitable equipment. For example, a system using evaporative condensers can attain primary energy ratio savings of 28.1% compared to conventional air-cooled condensers [11].

The energy savings resulting from system improvements can increase cold storage revenue, reduce expenses, and shorten the payback period. In addition, from an economic perspective, it is beneficial to provide premium prices to growers and offer farm products to consumers at competitive and affordable prices. However, the most important goal is to find the optimal relationship between investment cost and income. Therefore, it is necessary to determine the optimal storage capacity in which the investment is profitable. Generally, this type of investment has two cost items: the investment and annual operating cost. The cost of investment generally includes expenses such as land acquisition, building construction, permits and licensing, and water and electricity supply. The annual operating cost is composed of energy consumption, maintenance, indirect costs, etc. Therefore, correct storage techniques, selection of appropriate storage capacity, and suitable refrigeration system design should be considered together.

In this study, cold storage buildings with different capacities were investigated to determine the optimal cold storage capacity. To compare the selected cold stores, only those with similar specifications (type of building components, isolation, piping, refrigeration system components, etc.) were considered. All data were collected from an experienced refrigeration company, and apple production was then analysed according to economic indicators. All details of the cold storage building projects were examined, from the construction to the refrigeration system design and working principles. The research on the optimal storage capacity was conducted in two phases. The first was the evaluation of the relationship between the cold storage capacity and total system power consumption per unit volume and the factors affecting such relationship. The second phase involved the estimation of the payback period by calculating the cold storage building investment and operating cost. The profitable storage capacity for a sustainable cold storage building was analysed and solved using Monte Carlo (MC) simulation and net present value (NPV) methods. After applying the MC simulation using a period of 10 years, the cold storage buildings were ranked according to their payback periods, and the most profitable storage capacity was determined.

2. Materials and methods

2.1. Analysis of selected cold storage building projects

Applying the correct cold storage techniques is particularly important to protect the product for a long time, save energy, and reduce cost. Therefore, in this study, refrigerated plants that have been designed in accordance with the standards, especially new facilities, were selected. All components (compressors, evaporators, condensers, thermostatic expansion valves (TXVs), solenoid valves (SVs), receivers, panels, etc.) used in the cold stores were of the same quality and were from the same manufacturers. Therefore, there was no need to compare different warehouses of the same capacity. The cold stores were located in different regions and had similar features. In addition, all the warehouses stored the same product: apples. The apples are placed in the cold stores in October, and the amount of product in the cold stores decreases as it is sold. The cold stores are completely emptied in June.

The capacity of a refrigeration plant is based on a detailed heat load calculation for each project. The capacity calculations of all cold stores considered in this study were examined. According to the ASHRAE standard, the storage requirements of apples are +4 °C and 90–95% RH, and the specific heat capacity of an apple is 3.81 kJ/(kg·K) [12]. In this study, a bin was loaded with approximately 15–20 kg of apples. The above parameters and assumption were considered in the following equations.

Heat gain from transmission:

$$Q_{floor} + Q_{walls} + Q_{ceiling} = Q_{transmission}. \tag{1}$$

Heat load across walls:

$$q = UA\Delta t. \tag{2}$$

The thermal conductivities of polyurethane (0.025 W/(m·K)) and those of other wall materials were taken from ASHRAE tables [13].

Heat gain from infiltration:

$$q_t = q_a D_t D_f (1 - E). \tag{3}$$

Air exchange equation for a fully established flow [14]:

$$q_a = 0.221 A_d (h_i - h_r) \rho_r (1 - \rho_i/\rho_r)^{0.5} (gH)^{0.5} F_m, \tag{4}$$

where

$$F_m = \left[\frac{2}{1 + \left(\frac{\rho_r}{\rho_i} \right)^{1/3}} \right]^{1.5}. \tag{5}$$

Infiltration by direct flow through doorways:

$$q_i = vA_o(h_i - h_r)\rho_r D_d. \tag{6}$$

Product cooling load:

$$Q_{pr} = mc(t_1 - t_2). \tag{7}$$

Heat load due to personnel:

$$Q_{pe} = 272 - 6t. \tag{8}$$

Heat gains associated with equipment (fan motors, lighting, electric defrost system, forklifts, etc.) were also included in the calculations. The calculated cooling load was increased by 10%, to provide a safety factor for possible discrepancies between the design criteria and actual operation [13]. The specifications of the cold storage facilities selected for this study, which were verified by calculations, are presented in Table 1. The power values may vary between 3 and 5% depending on the instantaneous conditions.

To reduce the energy consumption caused by solar heat effects, cold stores are installed inside buildings, which are constructed of steel. For the thermal insulation in this application, the most ideal materials are polyurethane-filled sandwich panels. Therefore, the walls and ceilings of all cold stores consisted of prefabricated sandwich panels with polyurethane foam having a density of 40 ± 5% kg/m^3 between two galvanised steel sheets. The insulation was 100 mm thick, and the 0.50 mm galvanised steel sheets were painted on both sides with a polyester-based paint. The floor isolations were provided with polyurethane plates having a density of 40 kg/m^3. A general view of the refrigerated plants and cold stores is shown in Fig. 1.

Fig. 2 shows a plan of a cold store facility with a capacity of 1000 t of apples. The general structure of the other refrigerated warehouses is similar. The interior of the warehouse is divided into several rooms, which are maintained at a predetermined temperature by using adequate refrigeration equipment.

Ammonia is used as the refrigerant in the selected cold stores with capacities of more than 2000 t, whereas the small stores work with R404A. The operating conditions of the refrigeration system were set as -5 °C evaporation and $+40$ °C condensation. Humidification is performed in all cold stores using ultrasonic humidification devices. In addition, because the ethylene production rate in apples is very high, all stores had ethylene removal equipment to protect the quality of products stored by ensuring that the resulting ethylene gas from the preserved products is removed from the environment [13].

Fig. 3 shows the schematic piping and instrumentation (P&I) diagrams for single-compressor ammonia and Freon systems. Semi-hermetic compressors were used in the Freon refrigeration systems. Depending on the capacity, the number of compressors varied. The air-cooled condenser and evaporator heat transfer surfaces consisted of copper pipe and aluminium fins with high efficiency axial fans. The condenser pressure was kept constant by adjusting the fan speeds with a fan speed controller. Thus, the system performance was not affected by outdoor conditions. Electrical resistance heaters were used for defrosting. All refrigeration systems were also equipped with oil separators, suction accumulators, SVs, and TXVs. The refrigeration units employed a pump down system, which prevents catastrophic damage to the compressor when the system starts up. The superheat and subcooling values of the systems were 20 K and 5 K, respectively.

For the ammonia refrigeration systems, the number of reciprocating compressors depends on the capacity. The finned evaporators were manufactured from steel pipes with pressed steel fins. The evaporative condensers were equipped with hot galvanised steel pipe

Table 1
Capacity and specifications of cold stores.

Cold Store Capacity (t)[a]	Volume of Store (m^3)	Refrigeration System Capacity(kW)	Compressor Power Consumption(kW)	Condenser Fan Power (kW)	Evaporator Fan Power (kW)	Refrigerant	Store Location
100	480	36	12.4	2.25	2.72	R404A	Antalya, Turkey
500	2160	120	38.1	7	9.52	R404A	Konya, Turkey
800	4320	185	69.3	12	16.32	R404A	Karaman, Turkey
1200	6480	270	99.3	16	24.48	R404A	Nigde, Turkey
2100	11270	498	114	11	26.84	R717 (Ammonia)	Kayseri, Turkey
3500	18226	748	172	18.5	42.7	R717 (Ammonia)	Antalya, Turkey
4000	21600	870	197	30	48.8	R717 (Ammonia)	Isparta, Turkey
5000	25200	990	226	30	56.12	R717 (Ammonia)	Isparta, Turkey
6000	29100	1134	260	37	63.44	R717 (Ammonia)	Isparta, Turkey
8000	38200	1216	264	37	68.32	R717 (Ammonia)	Isparta, Turkey
10000	49680	1372	314	37	78.08	R717 (Ammonia)	Isparta, Turkey

[a] Tonnes of apples.

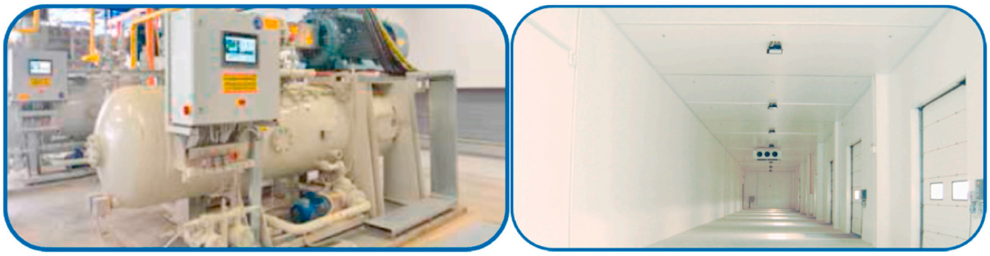


Fig. 1. General view of the refrigerated plants.

sections. The other auxiliary equipment used in the refrigeration systems included the compressor block with oil pump and filters, combined suction stop/check valves, ammonia pumps, and a receiver. In addition, according to the P&I diagrams, the systems were designed to be run automatically with automatic hot gas, suction pressure regulators, manually regulated valves, suction SVs, safety valves, and filters. All pipes were seamless steel according to DIN 2448 [15].

2.2. Cost analysis of cold storage buildings with different capacities

The optimal capacities of the cold storage buildings were investigated in terms of investment profitability. The MC simulation technique was used as an estimation tool. Simulation can be defined as a method of using models that represent real systems or processes to gain insights into these processes. Simulation models can be classified into two groups: deterministic and stochastic. The MC simulation relies on repeated random sampling and statistical analysis to compute the results and it is frequently used in stochastic engineering problems [16]. It can be defined as a numerical technique based on physical or mathematical models, which uses random numbers to solve static problems [17]. It involves representing the input and output parameters with a probability distribution (normal, lognormal, uniform, program evaluation review technique (PERT), etc.) rather than a single value. The input and output parameters of a specified event are defined in the system, and iterations are performed at random times to obtain results for certain possibilities. The flowchart for the solution method is presented in Fig. 4. First, input data for the key cash flow parameters, namely construction duration, nominal interest rate, inflation rate, apple sale price, annual expenditures, maximum price difference of apples in a year, amount of apples stored, and investment cost of the refrigeration plant, are collected from the projects.

Construction duration (n_c) refers to the total time required to build a refrigerated warehouse, including the construction and installation of refrigeration equipment. This duration was determined to be in the range of 1–6 months. The real interest rate is equal to the nominal interest rate, which is based on the general inflation rate in a country. For this study, the nominal interest rate and inflation rate were obtained from a 10-year period in Turkey and were assumed to range from 0.05 to 0.13 and from 0.04 to 0.20, respectively. Annual income (AI) refers to the profitability of offering apples at high prices in the period of supply shortage rather than selling the apples to the market at low prices during the harvest period. It is obtained by multiplying the apple sale price (p_a), price change of apples (pc_a), and amount of stored apples (s_a). Based on data collected for the last 10 years in Turkey, the apple sale price ranged from € 0.1 to € 0.3, with an average of € 0.2, whereas the price change of apples in a year ranged from 100% to 200%, with an average of 150%. The average amount of stored apples is measured in tonnes. The annual expenses (AE) of a refrigeration plant consist of cost items such as staff expenses, maintenance, repair, and electricity expenditures. On the other hand, the investment cost of constructing a refrigeration plant (ICRP) is equal to the total cost of land, cost of building construction, and costs of mechanical and electrical installations for the plant. Probability distributions for cash flow elements defined by the PERT and the normal distribution are listed in Tables 2 and 3, respectively. PERT is a type of beta probability distribution that is often used in various steps of project management. It is a modelling technique for estimating completion time or any other desired event based on the best estimates of the minimum, maximum, and most likely values for the event.

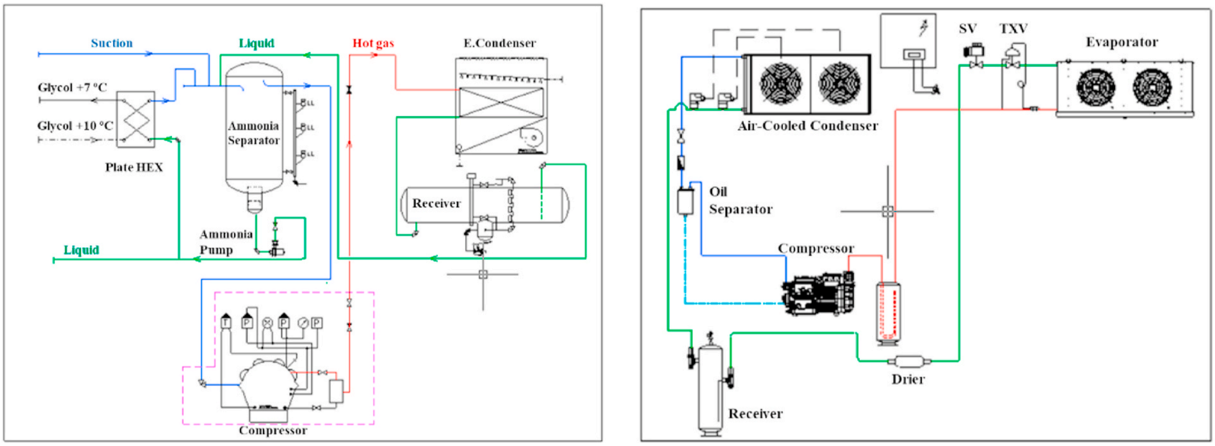
MC simulation with 5000 iterations was executed according to the obtained value ranges, defined probability distributions, and the NPV calculation shown schematically in Fig. 5 and described in Equation (9).

NPV in the nth year:

$$\mathrm{NPV_n} = \mathrm{ICRP} + \frac{\left[\sum_{n=1}^{10}\frac{\mathrm{AI_n}}{(1+\mathrm{i_r})^n} - \sum_{n=1}^{10}\frac{\mathrm{AE_n}}{(1+\mathrm{i_r})^n}\right]}{(1+\mathrm{i_r})^{\mathrm{n_c}}}. \tag{9}$$

These simulations and calculations were conducted using MS Excel and @RISK v5.5 software. The NPV value was calculated automatically for each year, and the earliest year when this value started to be greater than zero indicates the time when the investment of the plant building beg ins to be profitable. The payback period refers to the time when the entire investment is paid back. Therefore, the earlier the NPV value becomes greater than zero, the shorter the payback period, and the more profitable the plant investment.

Fig. 2. Plan of a cold store facility with a capacity of 1000 t of apples.



(a) **(b)**

Fig. 3. Schematic of the P&I diagrams for the a) ammonia and b) R404A refrigeration systems.

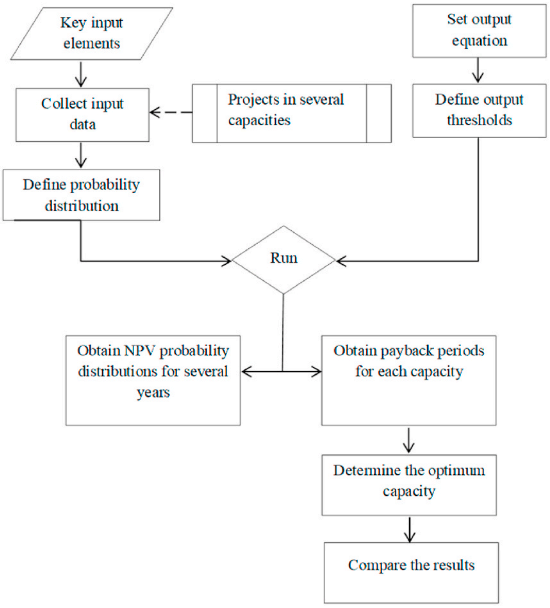


Fig. 4. Flowchart for the solution method.

3. Results and discussion

3.1. Effect of cold storage capacity on refrigeration unit power consumption

The relationship between the cold store energy consumption and store capacity was investigated. As shown in Fig. 6, the power consumption per unit volume of a cold store decreases as the storage capacity increases. In particular, for cold stores with capacities of 2100 t or greater, where an ammonia refrigeration system is used, an increase in the storage capacity has little effect on the power consumption.

To understand the effect of refrigerant type on the system power consumption in cold stores over 2100 t when R404A is used as a refrigerant instead of ammonia under the same conditions, a comparison of the total power consumption between ammonia and R404A refrigerants is depicted in Fig. 7. The higher power consumption of R404A is caused by its lower coefficient of performance (COP) compared to that of ammonia and the use of evaporative condensers in ammonia systems (Table 4).

Table 2
Probability distributions for cash flow elements based on PERT.

Cash Flow Parameters	Capacity (t)	Minimum	Most Likely	Maximum
Construction duration (n_c) (days)	100	30	35	40
	500	45	50	65
	800	60	65	75
	1200	65	75	80
	2100	80	85	95
	3500	95	105	115
	4000	105	110	125
	5000	110	125	140
	6000	120	135	150
	8000	140	150	160
	10000	185	195	210
Nominal interest rate (i_n)	–	0.05	0.09	0.13
Inflation rate (r)	–	0.04	0.09	0.20
Apple sale price (p_a) (€)	–	0.10	0.20	0.30
Price change of apple (pc_a)	–	100%	150%	200%
Annual expenses (AE) (€)	100	7090	7470	7710
	500	13760	14150	14550
	800	15620	16970	18500
	1200	19280	19930	21460
	2100	22120	23180	25380
	3500	42320	43720	44950
	4000	55270	58560	59910
	5000	66700	67590	69430
	6000	81530	82660	84880
	8000	88640	90320	92480
	10000	104920	107570	111070

Table 3
Probability distributions for cash flow elements defined by normal distribution.

Cash Flow Parameters	Capacity (t)	Mean	Standard Deviation
Amount of stored apple (s_a) (t)	100	100	10
	500	500	30
	800	800	50
	1200	1200	100
	2100	2100	150
	3500	3500	250
	4000	4000	270
	5000	5000	350
	6000	6000	450
	8000	8000	550
	10000	10000	700
Investment cost of refrigeration plant (ICRP)(€)	100	90450	520
	500	262720	1140
	800	388530	1520
	1200	547720	2080
	2100	832210	3570
	3500	1124090	5120
	4000	1482000	8460
	5000	2041490	10280
	6000	2715000	13440
	8000	4281000	17160
	10000	5201000	22710

3.2. Payback period of cold storage warehouse investment according to capacity

After simulating the cold store systems, the NPVs for the defined capacities for each year were obtained. A sample probability distribution calculation outcome for a plant with a capacity of 500 t is presented in Fig. 8.

As a result of the simulations, the probability of an NPV greater than zero for seven years is presented in Table 5. Then, according to these NPV results, the payback period for each plant was calculated.

As indicated in Table 6, the plant with a 3500 t capacity has the shortest payback period at 2.00 years. Based on the payback period of each plant, a capacity–payback period graph was plotted (see Fig. 9). Then, a polynomial curve was fitted for this graph ($R^2 = 0.5297$).

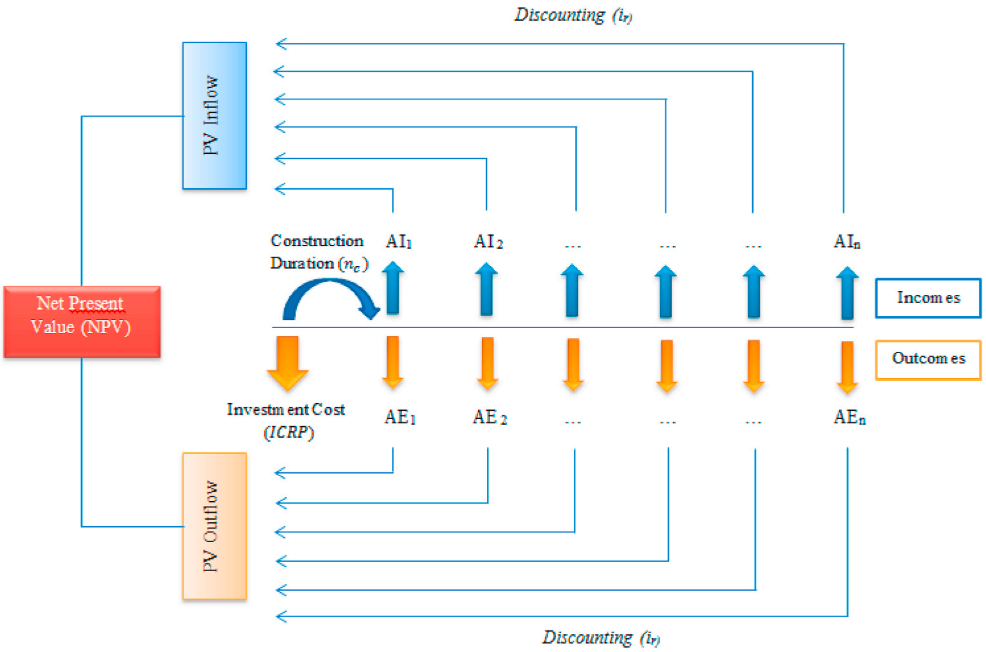


Fig. 5. Cash flow diagram.

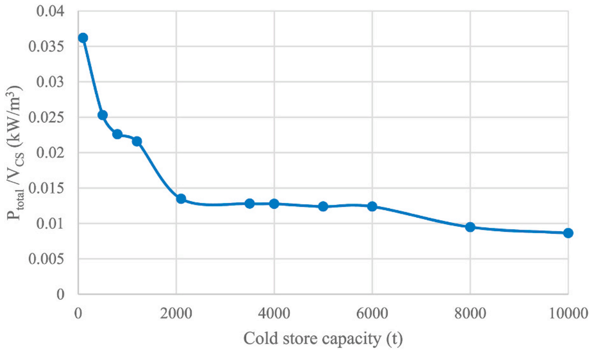


Fig. 6. Variation of power consumption per unit volume with cold store capacity.

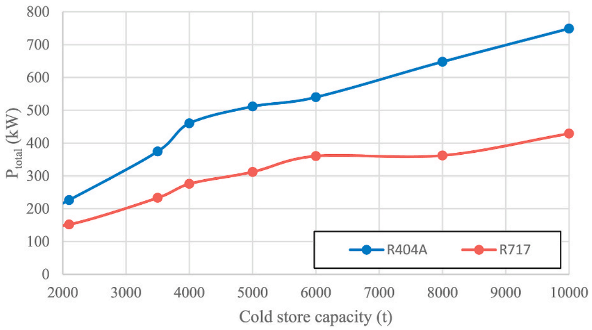


Fig. 7. Power consumption of refrigeration systems for R404A and R717 versus cold store capacity.

Table 4
COP and condenser fan power values for ammonia and R404A refrigeration systems with different cold store capacities.

Cold Store Capacity (t)	COP (ammonia)	COP (R404A)	Condenser Fan Power - R404A (kW)	Evaporative Condenser Fan Power - Ammonia (kW)
2100	4.36	2.58	20	11
3500	4.34	2.66	32	18.5
4000	4.41	2.55	48	30
5000	4.38	2.55	48	30
6000	4.36	2.70	48	37
8000	4.60	2.63	64	37
10000	4.36	2.46	80	37

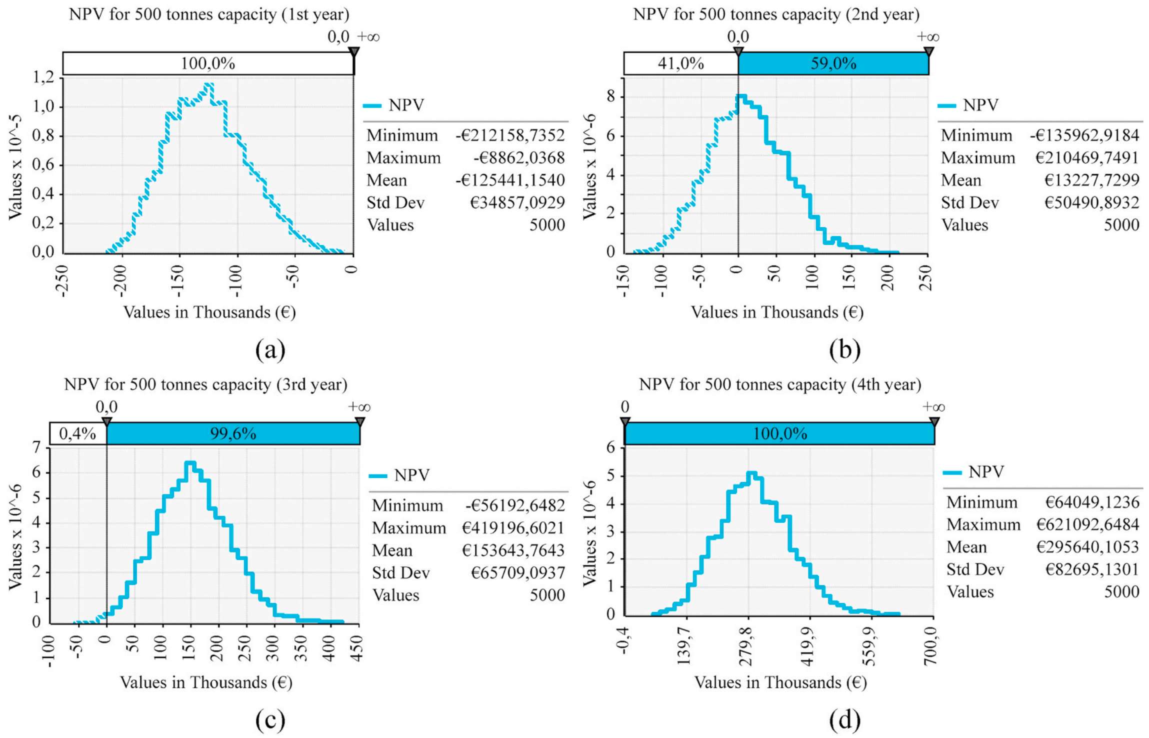


Fig. 8. Sample probability distributions of NPV for a capacity of 500 t: (a) 1st year, (b) 2nd year, (c) 3rd year, and (d) 4th year.

Table 5
Probability of the net present value (NPV) being greater than zero per year.

Capacity (t)	Probability of NPV > 0 (%) by years (%)						
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
100	0.0	0.0	5.7	53.8	92.3	99.6	100.0
500	0.0	59.0	99.6	100.0	100.0	100.0	100.0
800	0.2	77.9	99.9	100.0	100.0	100.0	100.0
1200	1.2	87.8	100.0	100.0	100.0	100.0	100.0
2100	7.9	97.7	100.0	100.0	100.0	100.0	100.0
3500	32.6	99.9	100.0	100.0	100.0	100.0	100.0
4000	14.2	98.7	100.0	100.0	100.0	100.0	100.0
5000	6.0	96.8	100.0	100.0	100.0	100.0	100.0
6000	2.6	90.0	100.0	100.0	100.0	100.0	100.0
8000	0.0	65.8	100.0	100.0	100.0	100.0	100.0
10000	0.0	61.4	98.0	100.0	100.0	100.0	100.0

4. Conclusion

Insufficient cold chain infrastructure is a major contributor to food loss. Therefore, it is important to encourage cold storage investments. To pave the way for this type of investment, uncertainties should be reduced through research studies.

Table 6
Payback period of the plants.

Capacity (t)	Payback Period (years)
100	6.04
500	3.00
800	3.00
1200	2.15
2100	2.03
3500	2.00
4000	2.02
5000	2.03
6000	2.11
8000	2.53
10000	3.06

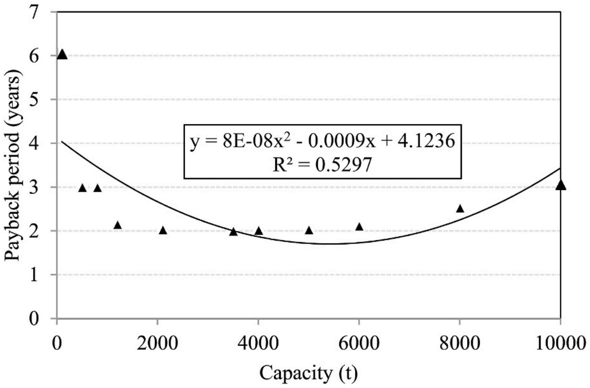


Fig. 9. Capacity–payback period chart.

Here, cold storage projects with different capacities were investigated, and the optimal storage capacity was estimated according to the data collected from the projects (investment costs, operating costs, specifications of the refrigeration system, etc.). First, the power consumed by the refrigeration systems in the selected cold stores was evaluated based on the capacity, and the effects of different refrigerants on the system were examined. According to the results, the calculated power consumption per unit volume is 63.8% for capacities between 100–2100 t, whereas this value is 33.3% for capacities between 2100–10000 t. Two of the factors causing this reduction in power consumption are the higher COP of ammonia compressors and the higher efficiency (by 35%) of evaporative condensers compared to air-cooled condensers.

Second, the investment decision for a cold storage warehouse was evaluated, and the profitability and payback periods were simulated using the MC technique. According to the results, while the payback period of the cold storage warehouse with a capacity of 100 t is approximately 6 years, it decreases to approximately 2 years for the 3500 t warehouse. At capacities above 3500 t, the payback period increases with the capacity. To generalise the results obtained from this study, different parameters, such as seasonal and regional climate changes and cold store usage conditions in different countries, must be investigated in future studies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

q: heat gain (W)
U: overall heat transfer coefficient (W/(m^2•K))
Δt: air temperature difference on either side of the wall (K)
A: outside area of section (m^2)
q_t: average heat gain over 24 h or another period (kW)
q_a: sensible and latent refrigeration load (kW)
D_t: doorway open-time factor
D_f: doorway flow factor
E: effectiveness of doorway protective device
A_d: doorway area (m^2)
h_i: enthalpy of infiltration air (kJ/kg)
h_r: enthalpy of refrigerated air (kJ/kg)
ρ_i: density of infiltration air (kg/m^3)
ρ_r: density of refrigerated air (kg/m^3)
g: gravitational constant (m/s^2)
H: doorway height (m)
F_m: density factor
q_i: average refrigeration load (kW)
v: average air velocity (m/s)
A_o: opening area (m^2)
D_d: decimal portion of time the doorway is open
Q_{pr}: heat removed (kJ)
m: mass of product (kg)
c: specific heat of product above freezing (kJ/(kg•K))
t_1: initial temperature of product above freezing (°C)
t_2: lower temperature of product above freezing (°C)
t: temperature of refrigerated space (°C)
NPV_n: NPV value for the nth year
$ICRP$: investment cost of refrigeration plant
AI_n: annual income for the nth year
AE_n: annual expenses for the nth year
i_r: real interest rate
n_c: duration of construction
n: calculated year
P_{total}: amount of power consumed by refrigeration system (kW)
V_{CS}: cold store volume (m^3)