Comparison of annual cooling energy demand between conventional and inflatable dock door shelters for refrigerated and frozen food warehouses

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Abstract

The aim of this study is to estimate the energy savings potential that can be achieved using inflatable dock shelters versus simple curtain dock shelters for loading/unloading activities in logistics warehouses. The article describes how these savings have been analysed and quantified in a big logistics centre of a Spanish dealer. It takes into account different refrigeration applications (i.e. for different warehouse dock temperatures), exterior conditions and daily loading/unloading schedules and their duration. We have used mean typical years for the different Spanish climatic zones, although the procedure can be easily extended to any climate. As expected, the greatest energy savings are achieved in the warmest climates with the coldest storage temperatures and for the nocturnal operations. The savings quantification allowed us to convince the owner to replace the conventional dock shelters.

Finally, the implementation of the procedure in a software-tool is helping other dealers to carry out a self-evaluation of the savings potential of their facilities.

Keywords: energy efficiency, efficient warehouses, loading docks, efficient docks.

Nomenclature

A $[m^2]$	Bare area of the dock door
CDD $[ºC]$	Cooling degree day with base 24ºC during June, July, August and September
E_f $[adim.]$	Effectiveness of doorway protection
E_{fan} $[kJ]$	Fan energy consumption
E_{fw} $[adim.]$	Average effectiveness of doorway protection in loading/unloading operation
E_{truk} $[kJ]$	Energy due to outdoor air infiltration into the truck when it opens its back doors
f_{load} $[adim.]$	Ratio of truck volume occupied by cargo
g $[m \cdot s^{-2}]$	Gravitation acceleration constant
H $[m]$	Dock door height
HDD $[ºC]$	Heating degree day with base 20ºC during January, February and December
h_{in} $[kJ \cdot kg^{-1}]$	Interior air enthalpy
h_{out} $[kJ \cdot kg^{-1}]$	Exterior air enthalpy
P_{inf} $[kW]$	Thermal load due to air infiltration
P_{fan} $[kW]$	Fan power
Q_v $[m^3 \cdot s^{-1}]$	Volumetric flow rate

$Q_{v,exp}$ $[m^3 \cdot s^{-1}]$ Experimental volumetric flow rate
$SRad$ $[kW \cdot h \cdot m^{-2}]$ Accumulated global radiation during June, July, August and September
$t_{operation}$ $[s]$ Average time needed for loading/unloading
v $[m \cdot s^{-1}]$ velocity
V_{truk} $[m^3]$ Truck volume
$WRad$ $[kW \cdot h \cdot m^{-2}]$ Accumulated global radiation during January, February and December

Greek symbols
ρ_{in} $[kg \cdot m^{-3}]$ Indoor air density
ρ_{out} $[kg \cdot m^{-3}]$ Outdoor air density
ρ $[kg \cdot m^{-3}]$ Density
ΔL $[m]$ Longitude tolerance
ΔA $[m^2]$ Area tolerance
Δv $[m \cdot s^{-1}]$ Velocity tolerance
$\Delta \rho$ $[kg \cdot m^{-3}]$ Density tolerance
$\Delta Q_{v,exp}$ $[m^3 \cdot s^{-1}]$ Experimental volumetric flow rate tolerance

1. Introduction

The constant increase in energy prices and the energy-saving policies adopted by governments in recent years are encouraging industries to seek to become more efficient in their energy consumption in order to improve their competitiveness. By installing the appropriate loading docks and using good door seals, industries can control cooling costs and, in some countries, they can even obtain financial incentives from their governments [1].

A bad seal of dock doors causes the cold air to leak out of the warehouse building during the loading/unloading operations. Simultaneously, warm outdoor air penetrates into the dock through any gap there may be between the seal and the fabric. In addition to the energy issue, this also represents a threat for chilled operations in food industries, since it makes it difficult to keep the temperatures within a specified range, thus increasing the risks of spoiling the products or affecting their quality and threating the trademark.

Moreover, if the outdoor air is very humid (in coastal locations, for example), then in the case of frozen products, ice appears in the evaporators increasing the amount of defrost cycles, leading to lower efficiency and product quality risks. The case of robotised warehouses is even worse. Ice formation on the rails of the automated trolleys causes unwanted stops and requires maintenance. Seeking a quick solution, the warehouse owner usually installs desiccant dehumidifiers. However, although this is an operative solution, it is very inefficient. It increases both energy consumption and the installed power and is quite expensive to maintain.

For these reasons, a great deal of energy, repair-time and money can be saved by reducing the infiltration of outdoor air through dock doors. There is a wide variety of dock-door types and even those that are similar include specific features added by each manufacturer. For this reason, it is necessary to describe the two dock types that were analysed and compared in this study. One dock-door is the one most commonly used in the logistics industry in Spain for refrigerated warehouses. The other includes some protection-enhancement features. Curiously, the latter is commonly used in very cold countries where, conversely, the problem is that the food could freeze, due to the cold outdoor air leaking into the dock.

In what follows, a methodology is shown with which to estimate the yearly energy savings when the conventional door seal is improved. Converting this energy demand into energy consumption or monetary savings involves many other aspects. Therefore, we will only focus on the energy demand reduction. The results are of use for the purposes of deciding whether the dock-doors should just be rehabilitated or refurbished.

Although the infiltration problem is frequently referenced in literature and its modelling equations are well established (i.e. [2], [3] and [4]), it is quite difficult to find an estimation of the year-long energy demand impact which is, in fact, the kind of information that the owner really needs. The analysis focuses on the Spanish climate zones, but everything can be adapted to other foreign climates: either by using a general climate classification based on the Spanish winter and summer severity concept (see the Spanish building code [5]), or just by applying the procedure to a certain weather data file.

Finally, the owner obviously needs a quick calculation, not a procedure. Therefore, some software was developed to estimate the energy demand savings in any climate. It only needs the hourly weather data file in DOE-2 [6] "bin" format.

2. Problem definition and preliminary considerations

2.1. Background

The most common type of dock-door installed in Spain uses a simple shelter system made up of three flexible flaps placed at both jambs and at the lintel of the door (see Figure 1). This system is very widespread because of its reduced price and easy maintenance. However, the current energy and global warming scenario led to a major Spanish food dealer asking us for a detailed analysis of the problem.

Figure 1: Exterior view of simple flaps dock

The fact that the structure of this conventional protection is so simple means that it can be easily improved in several ways. The proposed alternative solution is based on inflatable shelters (see Figure 2). Such a shelter was actually installed in one of the doors of a dock in a big logistics centre in Riba-Roja (Valencia, Spain). Firstly, it was necessary to estimate, empirically, the effectiveness of the protection of both shelters under certain conditions. Secondly, the study was extended to infer the potential yearly energy savings which could be obtained.

Figure 2: Exterior view of inflatable dock adjusted to the truck shape.

The inflatable shelter was installed for the purposes of testing: energy performance, resistance to wear, ease of loading/unloading operations, etc. The rest of the shelters were the simple flaps type.
The following section describes how the energy savings are calculated for each shelter type. Due to the peculiarities of this problem, certain hypotheses are needed. For example, the results are quite sensitive to the following operating conditions:

- dock's indoor temperatures.
- time duration of every operation and number of them per hour.
- time schedules of loading/unloading operations.

In our case, these data were provided by the manager of the logistics centre, who kept a register of the operations. Obviously, these data are different for each type of product (refrigerated or frozen). In order to evaluate the different scenarios, the developed software [7] implements a simple energy model which is described in the following section. The tool might also be useful for the purposes of optimizing the energy necessary for the daily time scheduling, if possible, of the loading/unloading operations.

2.2. *Loading/unloading process description*

The differences between using simple flaps or the inflatable shelter are not only to be found in the degree of protection they offer from o infiltration but also in how the loading/unloading processes are carried out. These differences have been taken into account when calculating the energy savings.

The loading/unloading process for the simple flaps shelter is as follows:

- The truck is positioned at some distance from the dock door with its back facing it.
- The driver climbs out and opens the back doors of the truck completely. Hot air unavoidably penetrates into the body of the truck, filling the volume not occupied by the cargo (see Figure 3).

Figure 3: Back doors of truck open approaching dock door

- The driver comes back, climbs into the truck and reverses it towards the dock door.
- The driver climbs out once again and goes into the warehouse to open the dock door.
- He takes the dock walkway out for loading/unloading purposes.
- Once the process is finished, the driver closes the dock-door and returns to the truck.
- Then he moves the truck forward, climbs out to close the back doors and leaves for his next destination.

This process is very time-consuming, regardless of the warehouse type, because of the need to open the back doors of the truck before connecting it to the dock. It allows the outdoor air to come into the trailer. In hot climates, like some parts of Spain, this is dangerous, because it could break the cold-chain.

The loading/unloading process using inflatable shelters has some differences which provide some advantages:

- The truck is positioned with its back facing the dock door and gets very close to the door. There is a thick rubber band below the door which absorbs the contact impact.
- When the back of the truck touches the doorstop springs (rubber bands), the driver climbs out and goes directly into the dock.
- Once inside, the driver pushes the button to start the fans and the shelter is inflated.
- Firstly, the driver opens the dock door and then opens the back doors of the truck, but this time the conditions are those of inside the dock.
- He takes the dock walkway out and into the truck for loading/unloading purposes.
- Finally, he closes the back doors of the truck and closes the dock door. After closing, the inflated shelter is switched off.
- Finally, he climbs into the truck and leaves for the next destination.

On the basis of the above descriptions, it is necessary to consider the following differences in the calculation of the energy savings when using the inflatable docks:

- The most important consideration is the difference between the amount of outdoor air that leaks into the warehouse dock despite the shelter during the loading/unloading. This amount is a function of what is known as the dock protection effectiveness (E_f).

- In the case of the flaps shelter, the amount of outdoor air coming into the truck box when the driver opens the back doors and reverses it towards the dock (see Figure 3). It is measured as a fraction of the truck body volume f_{load}. This fraction varies from a certain minimum value: 0 when unloading and 1 when the truck must be loaded. This amount is not present in inflatable docks since the back doors of the truck are opened inside the dock and the conditions inside the truck are similar to those in the warehouse. Thus, this energy exchange is neglected in inflatable dock doors. Figure 4 shows the interior view of the inflatable dock door.

Figure 4: View of inflatable dock from inside the warehouse

- The electrical energy consumption of the fan during the loading/unloading in the case of inflatable shelters does not exist when using simple flaps. However, the inflatable shelter needs a constant air flow to adapt its shape to the truck body and to seal any gaps. This constant air flow is supplied by a fan which is kept on during the whole operation. It has an electrical power of 1 kW.

2.3. *Warehouse and dock data*

Table 1 shows the values which were used in our case. The protection effectiveness values of both the inflatable and flaps shelters ($E_{inflatable}$, E_{flaps}) will be discussed in the Measurements section; some of them may have different values in each operation. For instance, an average time has been used for the loading/unloading procedures. Every operation has the same characteristics. In other logistics centres, this time may be different and should be adjusted.

Indoor temperatures	2.5ºC (frozen) and 10ºC (conservation)
Indoor relative humidity	68%
Truck volume	90 m³
f_{load}	0.85
Dock width	2.8 m
Dock height	3.3 m
P_{fan}	1000 W
$E_{inflatable}$	0.96
E_{flaps}	0.67
Average loading/unloading time	22 minutes

Table 1: Fixed input data for the study. The $E_{inflatable}$, E_{flaps} values are discussed in the Measurements section.

The analysis uses two indoor temperatures because the logistics centre has two types of warehouses: one for frozen food products (robotised warehouse), whose dock is kept at 2.5 ºC, and another for fruits and vegetables, whose dock thermostat is set to 10 ºC. Neither the former nor the latter have any relative humidity controls, but measurements show an average value of 68%.

3. Energy modelling of loading docks

A large amount of the energy consumed in refrigerated logistics warehouses is due to the infiltration of outdoor air through the dock-door when loading/unloading the trucks. The airflow volume due to the stack effect of the cold air can be estimated by the well-known Gosney and Olama [8], Eq.
(1. This expression quantifies the infiltration volume flow rate for typical doors when no protection is in place and neither is there any other obstacle (like the body of the truck). This analytical model has been verified in some experimental procedures and is highly accurate [4].

$$Q_v = 0.221 \cdot A \cdot (g \cdot H)^{0.5} \left(\frac{\rho_{in} - \rho_{out}}{\rho_{in}}\right)^{0.5} \left(\frac{2}{1 + (\rho_{in}/\rho_{out})^{0.333}}\right)^{1.5} \quad (1)$$

For a given airflow exchange, the thermal load can be estimated using Eq. (2, where the enthalpy difference between the outgoing and ingoing airflows is used [8].

$$P_{inf} = \rho_{in} \cdot Q_v \cdot (h_{out} - h_{in}) \quad (2)$$

In order to consider the obstacles or the shelter, Eq.(2 is commonly modified in the literature by using a multiplier named protection effectiveness, E_f. The value of this coefficient lies between 0 and 1 and this indicates the degree of protection that the door offers against the infiltration airflow; the higher the value, the better the protection. The application of this coefficient to Eq. (2 gives Eq. (3. The obstructions are the shelter devices of the dock door and the truck body.

$$P_{inf} = \rho_{in} \cdot Q_v \cdot (h_{out} - h_{in})(1 - E_f) \tag{3}$$

There are some authors who try to parametrize the value of the door protection effectiveness for different dock types [9] and [10]. All these studies have, mainly, analyzed the effectiveness of using air curtains or strip curtains. Unfortunately, there are no studies into inflatable shelters. In all likelihood, this is due to their recent introduction into the warm-climate market. Therefore, there are very few installations. To our knowledge, ASHRAE has developed a proposal [11] in which one of the objectives is literally to *"Measure the air infiltration of truck/trailer dock doors with a range of protection systems (e.g. inflatable cushions, bump cushions, flexible flaps) for a range of operating conditions"*.

As mentioned previously, each dock has a different operation scheme for loading/unloading. The energy losses at the dock door are thus evaluated as follows:

- The greatest loss of energy is due to the outdoor air infiltration. This loss is a function of the effectiveness (E_f) of the dock shelter devices. Moreover, the value of E_f may not be constant during the whole operation in the flaps case, because there are two stages; one when the dock walkway is extended and another when it is not. So, the value of E_{fw} considers this peculiarity by means of time weighting the E_f values in each stage during the operation. Taking this into account, Eq.(4 gives the energy cooling demand for the whole operation.

$$E_{inf} = \rho_{in} \cdot Q_v \cdot (h_{out} - h_{in})(1 - E_{fw})t_{operation} \tag{4}$$

- In the flaps case, the trucks must open their rear doors outside before docking. The cargo volume is filled with the exterior air. Afterwards, when the truck is connected to the warehouse, this volume of air is considered as a thermal load. This load is expressed as a function of the truck body's volume and the ratio occupied by the cargo f_{load}, Eq.(5.

$$E_{truck} = V_{truck} \cdot (1 - f_{load}) \cdot \rho_{out} \cdot (h_{out} - h_{in}) \tag{5}$$

- The energy consumed by the fan of the inflatable shelter is simply its power by the time needed to finish the loading/unloading.

$$E_{fan} = P_{fan} \cdot t_{operation} \tag{6}$$

4. Measurements

The fundamental purpose of the measurements and data collection was the calculation of the protection effectiveness of each type of door. Measurements were taken on July 2nd, 2010 at 10:30 am. The outdoor conditions in terms of temperature and humidity were 27ºC and 53% respectively. It should be noted that the indoor conditions of the dock showed significant oscillations during the loading/unloading operation due to outdoor air infiltrations when the doors with simple flaps were used. The indoor temperature set-point was fixed at 4.5ºC. The relative humidity was not controlled and its value was 68%, although it could reach 78% during loading/unloading. These data were used to estimate the maximum infiltration airflow rate, i.e. without obstacles, using the Gosney and Olama, Eq. *(1*.

The next step was to estimate the actual volumetric infiltration flow rate (Q_v). It was necessary to measure the air velocity through the spaces or gaps between the door fabric and the shelter as well as their cross sectional area. This area was estimated using a computerized treatment of the digital pictures: the biggest gaps were the two bottom corners (left and right), see Figure 5, and the cross sectional area of the dock walkway used for loading/unloading. The reference length was measured using a measuring tap class I. Its tolerance value was $\Delta L = 2.10^{-4}\ m^2$ .The value of the total opened section was A=0.382 m².

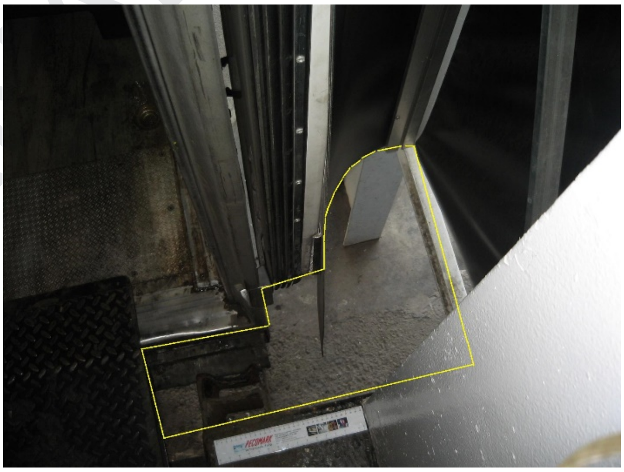
Figure 5: Main openings in a simple flaps dock door shelter

Inflatable docks provide a much better shelter since no gaps were visible even at the bottom (see Figure 6). From inside the dock, no sunlight could be seen passing through any gap.

Figure 6: Contact between the back of the truck door and the dock door.

Figure 5 shows the bottom gaps for the flaps shelter. This area is not always the same, since it depends on how good the contact between the truck body and the shelter is. Even the size of the body of the truck may vary. The accurate calculation of the air leakage section area is very difficult in practice, but assuming that the air flows along the path of least hydraulic resistance, and this happens at the bottom, the air velocity is measured just there. The hot wire anemometer measured velocities of between 2.5 m/s and 3.0 m/s; the average value measured during the process was 2.8 m/s. This measurement was obtained using a Testo 425 hot wire anemometer. Its tolerance was $\Delta v = 0.03$ m/s. The sensor was located in the centre of the section measuring the flow in a vertical downward direction. According to Eq. (7), the experimental infiltration volumetric flow rate estimated in the above conditions was 1.1 m^3/s.

$$Q_{v,exp} = \rho v \mathrm{A} \tag{7}$$

The precision of the volumetric flow rate depends on the accuracy of each one of the variables necessary for its calculation, Eq. (8).

$$\Delta Q_{v,exp} = \left|\frac{\delta Q_v}{\delta \rho}\right|\Delta\rho + \left|\frac{\delta Q_v}{\delta v}\right|\Delta v + \left|\frac{\delta Q_v}{\delta A}\right|\Delta A = v\mathrm{A}\cdot\Delta\rho + \rho\mathrm{A}\cdot\Delta v + \rho v\cdot\Delta A \tag{8}$$

The tolerance of the velocity, Δv, is obtained from the equipment specifications, as we mentioned previously. The tolerance of the section, ΔA, depends on the tolerance of the measuring tap. In a surface of 1x1 m., this value is $\Delta A = 2\cdot\Delta L = 4\cdot 10^{-4} m^2$. Although the surface value is lower, we take this tolerance value to ensure our measurement. Finally, the tolerance of the air density can be neglected. The example shown in [12] suggests a value of $\Delta\rho = 0.00054\ kg\cdot m^{-3}$. The estimated tolerance value for the experimental volumetric flow rate is $\Delta Q_{v,exp} = 0.01282\ m^3/s$ (or 1%).

Comparing the experimental infiltration volumetric flow rate with the Gosney and Olama, Eq. (1, the estimated value of effectiveness for the flaps shelter was around $E_f = 0.67$. This means that the flaps shelter permits an infiltration of about one-third of the maximum possible infiltration airflow rate calculated using Eq. (1. The value of effectiveness is obtained using Eq. (3.

Obviously, there is uncertainty in the effectiveness; this is not only due to the measurement procedure, but also to the position of the truck with respect to the door, the size of the truck body, the state of the flaps, etc. However, we are confident of the value because it is within the range of values indicated by [9] and [10] for similar door shelter types. These studies estimate this coefficient to be in the range of 60-80%.

The value of the protection effectiveness of the inflatable shelter is much more difficult to calculate because there are no clearly visible gaps. It would be necessary to take some controlled measurements with much more specific equipment (for instance a tracer gas). ASHRAE has an acceptance research topic (RTAR-1434) [11], whose aim is to obtain values for this type of shelter technology. Obviously, 100% protection is ideal.
The use of infra-red (IR) pictures taken from inside did not help us since they did not show hot spots which would point to hot air intakes (Figure 7 and Figure 8). In any case, inflatable and flaps shelters are hotter because they are outside the dock. Inflatable dock shelters are much less dependent on the size and the positioning of the truck body due to its auto-adjustment. The inflatable one, finally, was assumed to have stable protection effectiveness of 0.96 according to the best results obtained by [9] and [10] in other less effective solutions, e.g. strip curtains.

Although many IR pictures were taken to compare both systems, they were only used qualitatively to see the effect of each shelter on the incoming thermal radiation from outside and to detect how air flows. The conclusion was that both keep a hot zone around the truck body with a similar thermal radiation emission since both are made of plastic. Therefore, this effect was not expected to generate any significant differences in the cooling thermal load of the dock.

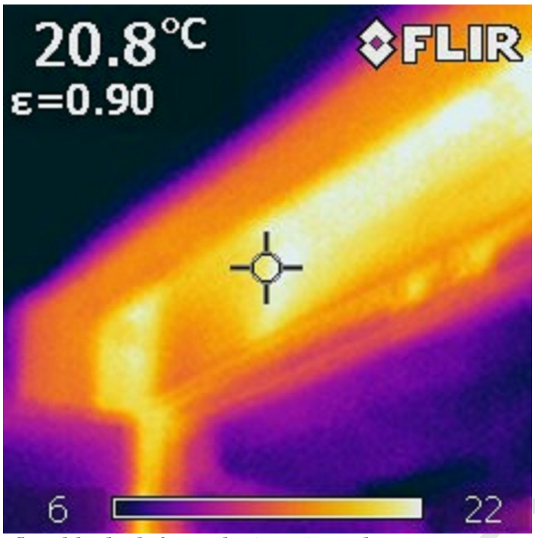

Figure 7: Infrared picture of the inflatable dock from the interior. The temperature shown corresponds to the cross at the center of the picture assuming an emissivity of 0.9.

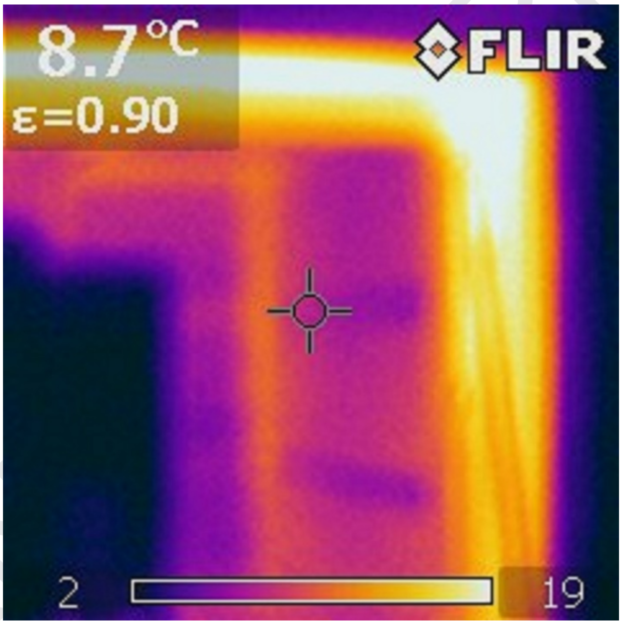

Figure 8: Infrared picture of the simple flaps dock from the interior . The temperature shown corresponds to the cross at the center of the picture assuming an emissivity of 0.9.

5. Impact on the cooling energy demand for different climate zones

Assuming the previous degree of protection against infiltration airflow rate for each type of shelter, we shall proceed to look at the change in the energy demand for different climate zones. The building code in Spain divides the country into different climate zones depending on the severity of summer and winter [5]. We have at our disposal hourly weather data files (8760 hours corresponding to a complete year) of each climate zone. These years are average or expected years, i.e. neither the hottest nor the coldest. Winter severity (SCI) is classified using letters, in increasing order of severity, from A (minimum winter severity) to E, whereas summer severity (SCV) is classified using numbers, from 1 (minimum summer severity) to 4. The weather in Madrid is taken as the reference severity.

The values of SCI and SCV are defined in Eqs. (9 and (10, and their values depend on global radiation and the value of degree days for winter or summer in each case.

$$SCI = -8.35 \cdot 10^{-3} \cdot WRad + 3.72 \cdot 10^{-3} \cdot HDD - 8.62 \cdot 10^{-6} \cdot WRad \cdot HDD + 4.88 \cdot 10 \cdot WRad^2 + 7.15 \cdot 10^{-7} \cdot HDD^2 - 6.81 \cdot 10^{-2} \quad (9)$$

$$SCV = 2.394 \cdot 10^{-3} \cdot SRad + 1.409 \cdot 10^{-2} \cdot CDD - 1.869 \cdot 10^{-5} \cdot SRad \cdot CDD - 2.053 \cdot 1 \cdot SRad^2 - 1.389 \cdot 10^{-5} \cdot CDD^2 - 5.434 \cdot 10^{-1} \quad (10)$$

Depending on the values of SCI and SCV obtained in Eqs. (9 and (10, the severity classification of climate data is obtained using Table 2 and Table 3. Each winter severity letter and summer severity number corresponds to a range of values of SCI and SCV, respectively.

A	B	C	D	E
$SCI \leq 0.3$	$0.3 < SCI \leq 0.6$	$0.6 < SCI \leq 0.95$	$0.95 < SCI \leq 1.3$	$SCI > 1.3$

Table 2: Winter Weather Severity

1	2	3	4
$SCV \leq 0.6$	$0.6 < SCV \leq 0.9$	$0.9 < SCV \leq 1.25$	$SCV > 1.25$

Table 3: Summer Weather Severity

Applying this methodology to any weather data, it could be classified with respect to Madrid's climate and, therefore, it would be possible to assimilate the results presented to the corresponding climate zone. In any case, for greater accuracy, it is possible to use any weather data in DOE-2 bin format to obtain the results by using the software [13].

6. Results

The following tables of results (Table 4, Table 5, Table 6 and Table 7) show annual energy losses for different daily time schedules of loading/unloading operations. These values have been obtained using the indoor conditions shown in Table 1, at two indoor dock temperatures: 2.5ºC and 10ºC. Each table contains a group of results for each climate zone described in Spain as an example. These groups of values correspond to the following energy losses:

- Flaps dock losses (GJ).

These losses include the effect of outdoor air infiltration through the shelter and that of the intake of outdoor air due to the truck-docking manoeuvres.

- Inflatable dock losses (GJ).

These losses include the effect of outdoor air infiltration through the shelter.

- Fan Energy Consumption (GJ).

Each operation in an inflatable shelter door needs the constant use of its fan.

6.1. Real warehouse schedule

Firstly, the schedule shown in Figure 9 represents a real schedule used by the warehouse in which the measurements were taken. The number of loading/unloading operations is 247 per day. This number of operations is the sum of all the dock doors belonging to the same warehouse. By analysing this schedule, it can be seen that most operations take place during the first ten hours of each day. This behaviour is not imposed by energy saving policies, but is rather due to the need to supply the shops in time.

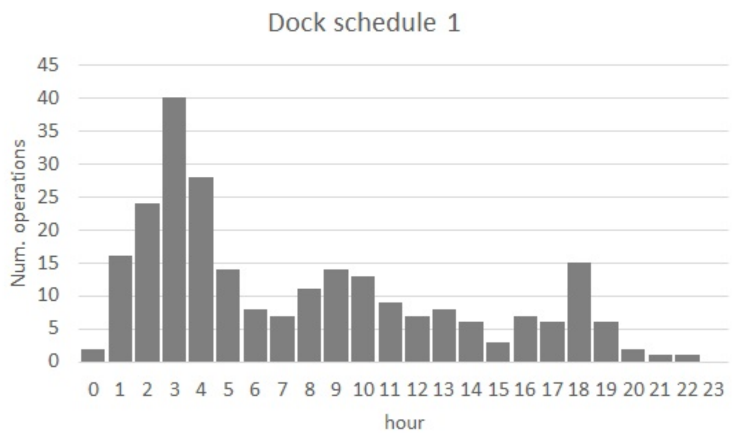

Figure 9: Loading/unloading schedule 1 (time in hours)

		T_dock=2.5ºC		T_dock=10ºC	
		Sensible (GJ)	**Latent (GJ)**	**Sensible (GJ)**	**Latent (GJ)**
A3:Tenerife	Flaps	2473	2296	1103	1183
	Inflatable	297	275	132	141
B3:Valencia	Flaps	1690	1578	648	728
	Inflatable	202	189	77	87
C2:Barcelona	Flaps	1483	1518	522	672
	Inflatable	178	182	63	80

D2:Cuenca	Flaps	940	579	328	107
	Inflatable	113	69	40	13
D3:Madrid	Flaps	1260	702	467	149
	Inflatable	151	84	56	18
E1:Burgos	Flaps	675	567	184	128
	Inflatable	81	68	23	15

Table 4: Annual cooling energy demand of the door shelters, for schedule 1.(Electrical energy consumption of fan 119(GJ).

As can be seen inTable 4, cooling energy demands are three or four times greater in hot climates than in cold ones (A3-the highest summer severity, E1-the highest winter severity). Tenerife, which is the reference for climate zone A3, has an average outdoor temperature of 21ºC. However, Burgos, which is used to represent climate zone E1, has an average outdoor temperature of 10ºC. Table 8 contains the average outdoor temperatures in each studied climate zone, for the purposes of comparing and observing the correspondence between these values and the results shown in Table 4, Table 5, Table 6 and Table 7.

Another noteworthy observation is the reduction in cooling demand when the temperature in the dock is higher. Cold locations are more sensitive to the temperature of the dock than hot ones. In hot locations, the energy demand more than doubles. Table 4 shows the results using two indoor temperatures, and the values obtained for an indoor temperature of 10ºC are significantly lower than the values obtained using a temperature of 2.5ºC.

As shown in Table 4, the difference between the values for the flaps and those for the inflatable shelter, respectively, represents the saving potential of the new shelter.

6.2. Afternoon warehouse schedule

The schedule shown in Figure 10 represents constant warehouse activity during the second half of the day. The distribution in Figure 9 presents the majority of the loading/unloading operations during the first half of the day while in this section we try to analyse the complementary situation, when this activity is concentrated during the afternoon and night.

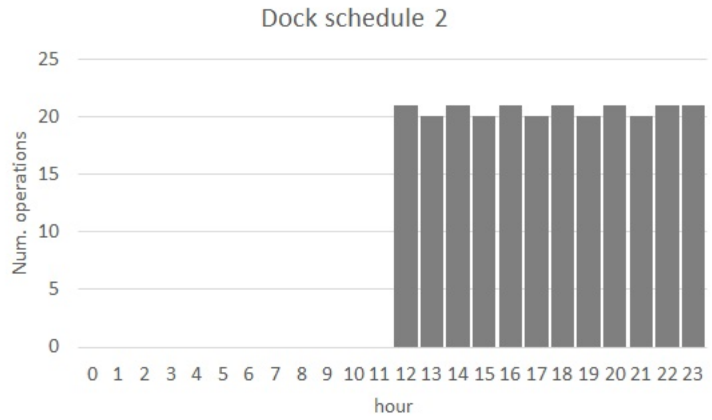

Figure 10: Loading/unloading schedule 2 (time in hours)

		T_dock=2.5ºC Sensible (GJ)	T_dock=2.5ºC Latent (GJ)	T_dock=10ºC Sensible (GJ)	T_dock=10ºC Latent (GJ)
A3:Tenerife	Flaps	2957	2445	1476	1313
	Inflatable	355	293	177	157
B3:Valencia	Flaps	2254	1759	994	845
	Inflatable	270	211	119	101
C2:Barcelona	Flaps	1925	1712	775	805
	Inflatable	231	205	93	96
D2:Cuenca	Flaps	1464	671	615	110
	Inflatable	175	80	74	13
D3:Madrid	Flaps	1742	730	748	117
	Inflatable	209	87	90	14
E1:Burgos	Flaps	1100	734	393	204
	Inflatable	132	88	47	25

Table 5: Annual cooling energy demand of the door shelters, for schedule 2.(electrical energy consumption of fan 119(GJ))

Greater losses are obtained using this schedule (Table 5) than in the previous case. This is due to the fact that the outdoor temperature values are higher in the afternoon, when the operations take place. Hence, the difference between indoor and outdoor temperatures is more marked and the loads caused by air infiltration increase. Obviously, this behaviour is shared by every climate zone.

6.3. *Constant warehouse schedule*

This case considers constant warehouse activity during the whole day. All 247 loading/unloading operations are distributed over 24 hours (see Figure 11). It represents an average of 10-11 operations per hour. The objective is to analyze the results using a constant distribution.

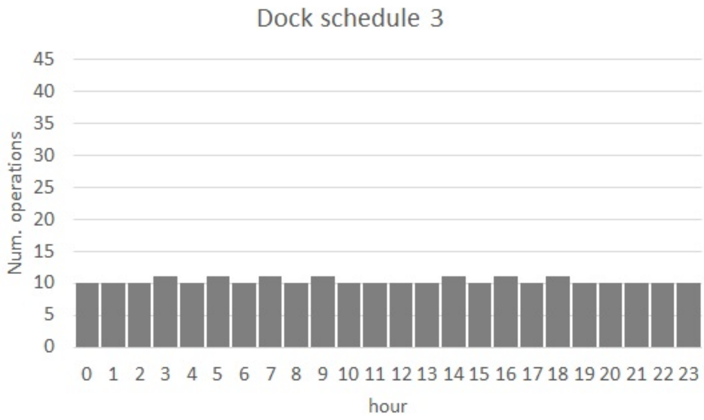

Figure 11: Loading/unloading schedule 3 (time in hours)

		T_dock=2.5ºC		T_dock=10ºC	
		Sensible (GJ)	**Latent (GJ)**	**Sensible (GJ)**	**Latent (GJ)**
A3:Tenerife	Flaps	2625	2344	1221	1224
	Inflatable	315	281	146	146
B3:Valencia	Flaps	1886	1644	767	772
	Inflatable	226	197	92	92
C2:Barcelona	Flaps	1641	1591	611	722
	Inflatable	197	191	73	86
D2:Cuenca	Flaps	1121	610	426	109
	Inflatable	134	73	51	13
D3:Madrid	Flaps	1427	709	563	137
	Inflatable	171	85	68	17
E1:Burgos	Flaps	821	627	254	157
	Inflatable	98	75	31	19

Table 6: Annual cooling energy demand of the door shelters, for schedule 3.(Eectrical energy consumption of Fan 119(GJ)).

Table 6 shows values of losses that are better than the previous case, but worse than the first one. It is discussed above; the losses are directly related to the outdoor air temperature, so these depend on the climatic conditions. The highest outdoor temperature values in every climate zone appear in the afternoon, so the losses will be greater when a major number of loading/unloading operations take place at this moment. For this reason, the first schedule (Figure 9), which groups the operations together in the morning, has better results than the second one (Figure 10), which groups together these movements in the afternoon. The constant schedule (Figure 11) distributes the operations evenly during the day and so it is logical that the results have values between both distributions.

6.4. *Night warehouse schedule*

In terms of energy, a night loading/unloading schedule is the best option (Figure 12). Based on this schedule, activities start each day at 8:00 p.m. and finish at 7:00 a.m., when the outdoor temperatures are lower and, therefore, loads due to air infiltration are lower.

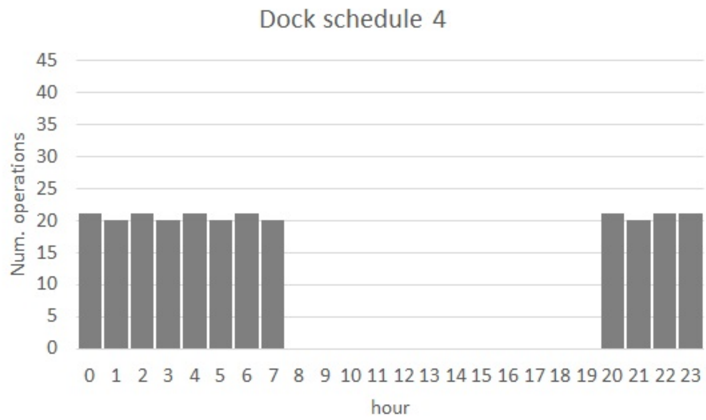

Figure 12: Loading/unloading schedule 4 (time in hours)

		T_dock=2.5ºC Sensible (GJ)	T_dock=2.5ºC Latent (GJ)	T_dock=10ºC Sensible (GJ)	T_dock=10ºC Latent (GJ)
A3:Tenerife	Flaps	2299	2250	967	1142
	Inflatable	276	270	116	136
B3:Valencia	Flaps	1383	1490	446	670
	Inflatable	166	178	53	80
C2:Barcelona	Flaps	1229	1404	365	591
	Inflatable	147	168	44	70
D2:Cuenca	Flaps	653	565	162	130
	Inflatable	78	67	20	16
D3:Madrid	Flaps	1013	725	312	194
	Inflatable	121	87	38	23
E1:Burgos	Flaps	445	484	63	92
	Inflatable	53	58	8	11

Table 7: Annual cooling energy demand of the door shelters for schedule 4.(Electrical energy consumption of Fan 119 (GJ)).

It is likely that this time schedule is not possible in some warehouses, but results show that when most operations take place during night hours, the energy losses are reduced. This is due to the fact that the outdoor temperatures are lowest at these times. This scenario presents reduced energy losses in every climate zone, the reduction ratio being greater for climate zone E1, the losses of are reduced by half with respect to the current schedule.

Climate zone and city	Average outside temperature ºC

A3:Tenerife	21
B3:Valencia	17
C2:Barcelona	15
D2:Cuenca	14
D3:Madrid	12
E1:Burgos	10

Table 8: Average annual outdoor temperature for each climate zone

7. Conclusion

The results set out in the previous section compare two types of loading dock doors located in different climate zones and working at two different indoor temperatures (for refrigerated and frozen food products).

The annual energy savings achievable using the inflatable shelter technology are not negligible. The main goal of these shelters is to reduce the outdoor air infiltration into the dock. The case analyzed in the article shows energy savings of around 88% compared to the traditional flaps shelters. This is very important for big logistics centres. Inflatable docks have an additional electrical consumption due to the fans, but this is not a determining factor. The reduction in outdoor air infiltration decreases the frequency of defrosting cycles and moderates the use of dehumidifiers to prevent the appearance of ice in automated docks.

Logically, the energy savings are greater in the hottest climates, such as zone A3, (Tenerife) and smaller in the coldest zones (Burgos). However, unlike other studies, we propose a means of quantizing them. In our experience, this actually serves as a stimulus for replacing the shelters.

Improving the shelter using a better technology, such as inflatable docks, could be very cost-effective in hot/warm zones. Its use for frozen products is wholly advisable.

Another interesting point is the indoor temperature set-point. The results show the sensitivity to this value. Whenever possible, the impact of increasing the dock temperatures by a few degrees can be evaluated for the traditional flaps shelters.

Most cold stores cannot decide to change their dock schedules as they wish, because they depend on externalities. However, a good policy using an appropriate schedule might have an important effect on reducing the energy consumption and the maintenance costs of the docks. It is important for the warehouse manager to be aware of this fact in order to help in making decisions. A schedule concentrated in the afternoon (Figure 10), which brings together all the operations during the second half of the day, leads to the highest losses and, moreover, they can be evaluated.

In brief, the main conclusion which can be extracted is that the methodology shown can be easily used to measure the actual energy savings that a better shelter can provide (although here we have not included the reduction in maintenance or the improvement in the security of the cold chain). Moreover, the method can provide an idea of the sensitivity of the energy savings to certain operative schedules or thermostat set-points, thus helping in the decision-making process.

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Declarations of interest: none

- Comparison of annual cooling energy demand between conventional and inflatable docks.
- Analysis of the influence of different schedules on energy demand.
- Description of the methodology used to calculate the outside air infiltrations.
- Comparative results for different climatic zones.