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Investigation of Spatial Variability of Air Temperature, Humidity and Velocity in Cold Stores by Using Management Zone Analysis

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ABSTRACT

The main objective of this research was to determine spatial variability of ambient temperature, relative humidity and air velocity in a cold storage using management zone analysis methods. Ambient temperature, relative humidity and air velocity of an experimental cold store were measured using 36 temperature-relative humidity sensors and air velocity measurement probe. Sensor installation was performed on grid scale at three levels (base, middle and top) such as to monitor the storage conditions in the cold store. The measured data were analysed by MZA software which performed fuzzy clustering to delineate the full cold storage, half full cold storage and empty cold storage. In addition, Surfer mapping software was utilized to create the maps of the measured parameters. The results indicated that there is significant spatial variation of the basic storage parameters such as ambient temperature, relative humidity and air velocity in the cold storage, which denotes the significance of management zones delineation in these facilities so as to maximize the storage.

Keywords: Cold storage; Management zones; Fuzzy clustering

Soğuk Hava Depolarında Hava Sıcaklığı, Nemi ve Hızındaki Konumsal Değişkenliğin Alansal Analiz Yöntemi İle İrdelenmesi

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ÖZET

Bu araştırmanın temel amacı, bir soğuk hava deposunda Alansal Analiz Yöntemini kullanarak ortam sıcaklığı, bağıl nem ve hava hızının konumsal değişkenliğini belirlemektir. Deneysel soğuk hava deposunun ortam sıcaklığı, bağıl nemi ve hava hızı, sıcaklık ve nemi aynı anda ölçen ve kaydeden 36 adet sensör ve hava hızı ölçüm cihazı kullanılarak ölçülmüştür.

Sensörlerin yerleşimi soğuk depolama koşullarını izlemek için üç seviyede (alt, orta ve üst) ızgara (grid) şeklinde yapılmıştır. Tam dolu, yarı dolu ve boş soğuk hava deposu için ölçülen veriler bulanık kümeleme yöntemi ile gruplama yapan Management Zone Analyst (MZA) yazılımı ile analiz edilmiştir. Ayrıca, Surfer haritalama programı ile ölçülen parametrelerin haritalarını oluşturmak için kullanılmıştır. Sonuçlar, soğuk hava deposunun verimliliğini en üst düzeye çıkarmak ve depolama süresini uzatmak için önemli temel parametrelerden olan ortam sıcaklığı, bağıl nem ve hava hızı dağılımı açısından önemli mekansal (konuma bağlı) farklılıkların olduğunu göstermiştir.

Anahtar Kelimeler: Soğuk depolama; Alansal işletmecilik; Bulanık kümeleme

1. Introduction

All fruits and vegetables have a 'critical temperature' below which undesirable and irreversible reactions or 'chill damage' takes place. Storage temperature always has to be above this critical point. In many cases, even though the thermostat is set at a temperature within the critical temperature limits, the thermostatic oscillation in temperature does not result in storage temperature falling below the critical temperature. Even 0.5 °C below the critical temperature can result in chill damage. For most products, high, but not saturated relative humidity is required, eg. 85-95%. There is always some moisture loss during cold storage, but excessive moisture loss is a problem. It is essential that relative humidity is kept above 85% (CSFV 2013).

The maintenance of an average temperature which is limited by a maximum temperature deviation is the main objective of temperature control in cold storage systems. Spatial and temporal variability is widely used for determining soil characteristics in agriculture (Ozgoz, et al., 2012). Determination of the spatial distribution of cold storage factors such as air velocity is useful to apply the best management techniques for storage of products (Akdemir & Arin 2005**).** Air flow inside a cold storage is investigated using computational fluid dynamics. The forced-circulation air cooler unit is modelled with an appropriate body force and resistance, corresponding to the characteristics of the fan and the tube-bank evaporator (Arkema et al 1999). In a climate chamber, eight identification experiments were carried out to model the spatiodynamic temperature response around plants to variations in the supply air temperature. From the experimental data, a minimally parameterized, linear, discrete–time transfer function matrix (TFM) model was identified, capturing the dominant model behaviour of the dynamic (Boonen et al 2002).

It is of great importance to analyse the spatial distribution of the cold store parameters. Thus, zones of different characteristics or management needs within the cold store may be delineated. Clustering techniques may be a basis for delineating zones. Cluster analysis is a technique which classifies data of many variables in discrete classes or clusters. The k-means (also known as c-means) is the most important non-hierarchical clustering. In k-means multidimensional data are classified into k classes (clusters) so as the centroid in each class has the minimum Euclidean distance from each data point. Extension of k-means clustering, are the non-parametric density algorithms of Fuzzy k-means that account for uncertainties associated with class boundaries and membership (Dobermann et al 2003) and are some of the most commonly used clustering techniques (Guastaferro et al 2010; Tagarakis et al 2013).

The software (MZA) exported two indices, FPI (Fuzziness Performance Index) and NCE (Normalized Classification Entropy) which indicated in how many zones the delineation was more distinct. The values of FPI ranged between 0 and 1. It is an index that measures the degree of separation between the fuzzy c-partitions of Y (Odeh et al 1992; Boydell & McBratney 1999). According to Fridgen et al (2004), the classes are distinct with less membership sharing when the FPI values approach 0. The NCE index measures the amount of disorganization of a fuzzy c-partition of Y (Odeh et al 1992; Lark & Stafford 1997). The optimum number of zones is achieved when both indices present minimal values (Tagarakis et al 2011).

Seppä et al (2013) used hierarchical cluster analysis to categorize the storage induced sensory changes of Finnish apples of twelve different cultivars, evaluated at 3 to 5 storage points during 8 - 17 weeks. They analysed 15 fruit attributes related to odour, texture, flavour and deterioration of the fruits and used cluster analysis on attribute intensities to reveal distinctive clusters. They concluded that cultivar and storage time are the main factors that shape the sensory properties.

The main objective of the current research was to use the management zone analysis methods (fuzzy clustering algorithms) in a cold store to determine and manage spatial variability of the three main storage attributes, ambient temperature, relative humidity and air velocity and delineate zones of differential management.

2. Material and Methods

An experimental cold storage was facilitated with 36 sensors installed in three levels (base, middle and top; 12 sensors in each level) on a grid (1.75 X 1.50 m) to measure and constantly monitor the above parameters in each sensor location.

2.1. Experimental cold store

The experimental cold store and air conditioning unit are given in Figure 1a and 1b. The system consists of water cooling unit, air conditioning unit and control unit.

Size of the cold store (length, width, and height) 4 x 5 x 3 m. Working temperature and relative humidity can be adjusted between 0°C and +30 °C, and 55 – 95%, respectively.

Cold air is distributed by the inlet (pressure) air channels and is aspirated by the outlet (suction) air channels to be released outside (Figure 2a, b). There are 3 inlets for distribution of the cold air and 3 outlets for suction of the exhausted air in the cold store.

The cooling system was facilitated with a vapour humidification unit. Its capacity was 2 kg h^{-1}. A control programme was responsible for the supervision and inspection of the cooling system performance. Inlet and outlet temperature and relative humidity could be controlled and checked on the screen. In case of malfunction the control unit showed a warning message.

(a) (b)

Figure 1- Experimental cold store (a) and air conditioning unit (b)

Şekil 1- Deneysel soğuk depo (a) ve hava şartlandırma ünitesi (b)

Figure 2- Air pressure channels (a) and air suction channels (b)

Şekil 2- Hava basma kanalları (a) ve hava emme kanalları (b)

2.2. Sensors

Temperature and relative humidity were measured by Testo 177H1 sensors. Air velocity was measured by using Testo 435 sensor.

The sensors (36 sensors in total) were installed in three levels (base, middle and top level; 12 sensors in each level) on a grid consisted of 12 measurement points (spaced 1.75 x 1.50 m) 4 in width and 3 in length, to measure and constantly monitor the above mentioned parameters in each sensor location. This specific sensor installation was selected so as to facilitate the mapping and zoning procedure (Figure 3).

The recommended conditions for commercial storage of apples are -1 °C to 4 °C and 90 to 95% RH, depending upon variety (Watkins et al 2004). Cooling system temperature and relative humidity were set at +2 °C and 95% respectively.

2.3. MZA software

Management Zone Analyst calculates descriptive statistics, performs the unsupervised fuzzy classification procedure for a range of cluster numbers, and provides the user with two performance indices (fuzziness performance index (FPI) and normalized classification entropy (NCE) to aid in deciding how many clusters are most appropriate for creating management zones (Fridgen et al 2004).

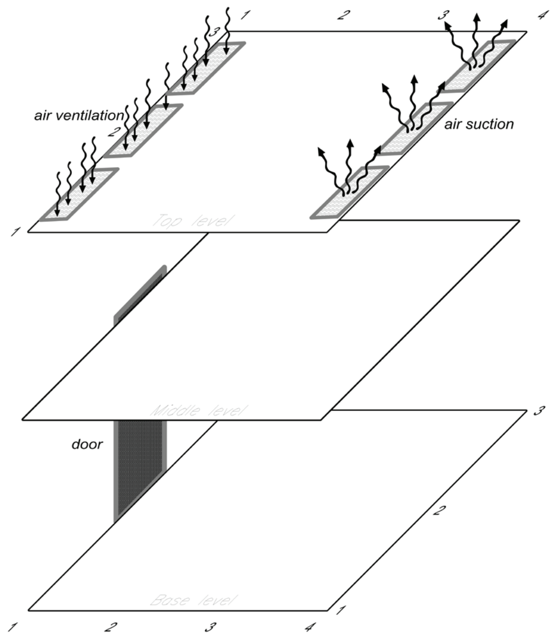


Figure 3 - Sensors' locations in the experimental cold storage

Şekil 3- Deneysel soğuk depoda sensörlerin yerleşimi

The FPI is a measure of the degree of separation between fuzzy c-partitions of the data matrix and is defined as Equation 1.

$$FPI = 1 - \frac{C}{(C-1)}\left[1 - \sum_{k=1}^{n}\sum_{i=1}^{c}(u_{ik})^2/n\right] \quad (1)$$

Where; u_{ik} ($1 \leq i \leq c$, $1 \leq k \leq n$) (1 is the membership value to the *i*th cluster centter in the cluster centroid matrix for the *k*th observation in data matrix;c is the number and n is the number of the observations.

The classification entropy (H) is defined by the function

$$H(U;c) = -\sum_{k=1}^{n}\sum_{i=1}^{c} u_{ik} log_a(u_{ik})/n \qquad (2)$$

Where; U is a fuzzy membership matrix, and logarithmic base a is any positive integer.

In Equation (2), H equals O when c is 1 or n, which is an obvious contradiction. Thus, Bezdek (1981) propounded the conception of normalized classification entropy (NCE).The NCE models the amount of disorganization of a fuzzy c-partition of the data matrix and is described as

$$NCE = H(U;c)/[1 - c/n] \qquad (3)$$

The values of FPI and NCE close to 0 mean small membership sharing and a large partition component, indicating good classification can be obtained when both FPI and NCE have minimum values in the class. Additional verification is required t determine how many clusters are to be used to create management zones when both performance indices have different numbers of zonning (Fraisse et al 2011)

2.4. Apples

Granny Smith apple variety was used to examine the storage scenarios of the experiment.

2.5. Methods

All the data from the three measured parameters were elaborated using fuzzy clustering to delineate zones for each level.

A first visual representation of spatial variability of the measured parameters was provided by the maps created for each level using Surfer mapping system. Management zones were created for all levels (bottom, middle and top) and for all scenarios (full, half full and empty cold storage) using MZA (Management Zone Analyst) software. For the delineation of the zones all three measured parameters were analysed together and therefore these zones represent the combination of the spatial variances of temperature, relative humidity and air velocity.

3. Results and Discussion

Ambient temperature, relative humidity and air velocity results are given in Table 1. Variation of ambient temperature and relative humidity in full and half loaded cold storage was higher than empty cold storage as a result of the agricultural product storage load. During storage, agricultural products continue to respire resulting an increase in temperature and decrease in relative humidity of cold storage. This statement was confirmed by the high coefficient of variation (Table 1). Similarly, air velocity spatial variation was higher in full and half full storage compared to empty storage because the fruit boxes obstructed air distribution in cold storage. Management zone analysis in cold storage management is novel and useful approach for better storage efficiency. The awareness of the areas of uneven temperature, relative humidity and air velocity can be used to find solutions for better preservation of the stored fruits, such as selective storage i.e. storing the loads at the zones with the most appropriate storing conditions, or upgrade the cooling system to optimize storage conditions at the zones showing poor storage conditions.

3.1. Empty cold storage

According to the maps for empty cold storage (Figure 4a, b, c), air temperature was homogenous in the entire storage for the three levels showing very low spatial variation which was confirmed by the low C.V. (0 – 1.6%) and the low range of measurement values (0 – 0.1 ^{o}C).

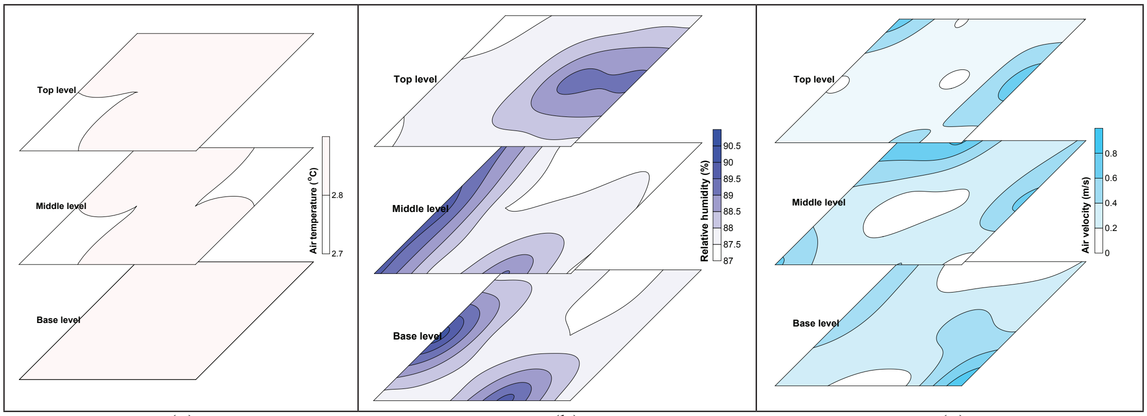
Temperature of base level in particular was totally homogenous in the whole surface (range equals zero). Relative humidity also showed remarkably low spatial distribution (C.V. ranged 0.75 – 1.13%) showing only 2 - 3% range. On the other hand air velocity showed quite high spatial variability mainly in the base and middle levels.

The bottom level could not be seperated into zones since spatial variability of the measured parameters was very low. Thus FPI and NCE indices were

Table 1- Relative humidity (%), Temperature (°C), and Air Velocity (m s^{-1}) descriptive statistics for full, half full and empty cold storage

Çizelge 1- Dolu, yarı dolu ve boş soğuk depo için bağıl nem (%),sıcaklık (°C), ve hava hızının (m s^{-1}) tanımlayıcı istatistikler

	Top level			*Middle level*			*Base level*		
	RH(%)	*t(°C)*	*V(m s^{-1})*	*RH(%)*	*t(°C)*	*V(m s^{-1})*	*RH(%)*	*t(°C)*	*V(m s^{-1})*
Full cold storage									
Minimum	81.38	3.60	0.02	84.46	3.60	0.04	81.43	3.45	0.06
Maximum	86.55	4.42	0.44	86.86	4.16	0.57	87.93	4.09	1.37
Std dev	1.63	0.24	0.11	1.03	0.13	0.15	1.66	0.19	0.43
Mean	84.74	3.96	0.18	85.79	3.79	0.21	85.96	3.74	0.47
C.V.	1.92	6.06	63.84	1.20	3.46	72.02	1.93	5.00	91.27
Half full cold storage									
Minimum	80.80	4.00	0.06	80.80	4.00	0.10	80.70	4.00	0.16
Maximum	85.90	4.70	0.56	86.00	4.70	1.52	89.90	5.70	1.00
Std dev	2.42	0.29	0.18	2.52	0.29	0.40	3.03	0.44	0.24
Mean	83.83	4.29	0.25	83.85	4.29	0.40	83.03	4.56	0.47
C.V.	2.88	6.84	73.44	3.00	6.84	100.00	3.64	9.74	51.48
Empty cold storage									
Minimum	87.30	2.80	0.16	87.30	2.80	0.08	87.40	2.80	0.02
Maximum	89.30	2.90	0.78	89.90	2.90	0.86	90.40	2.80	1.03
Std dev	0.66	0.05	0.21	0.99	0.05	0.27	0.99	0.00	0.28
Mean	87.87	2.83	0.35	88.14	2.83	0.41	88.02	2.80	0.34
C.V.	0.75	1.60	60.83	1.13	1.60	65.86	1.12	0.00	83.82



(a) (b) (c)

Figure 4 - Contour maps of temperature (°C) (a), relative humidity (%) (b) and air velocity (m s^{-1}) (c) for top, middle and base level in empty cold storage

Şekil 4- Boş soğuk depo içinde üst, orta ve alt seviyeler için sıcaklık (°C) (a), bağıl nem (%) (b) ve hava hızının (c) kontur haritaları (m s^{-1})

calculated only for middle and top level. According to the indices (Figure 5) the three zone delineation was the best option for the empty cold storage.

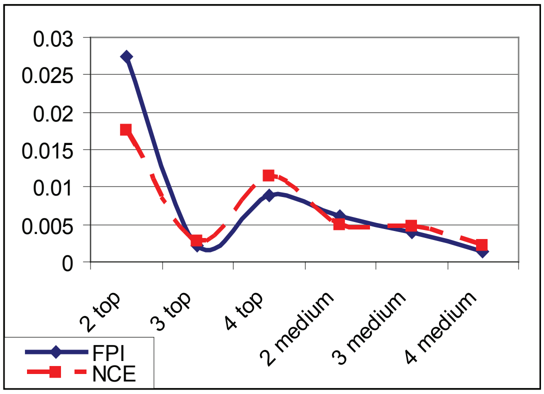


Figure 5 - FPI and NCE indices for 2, 3 and 4. zones delineation for the top and middle level

Şekil 5 - Üst ve orta seviye için 2, 3, ve 4. bölgelerin tanımlanması için FPI ve NCE indisleri

The final zone maps (Figure 6) were created using fuzzy clustering algorithms. According to the delineation, the base level was homogenous while the middle and top levels were seperated into three zones.

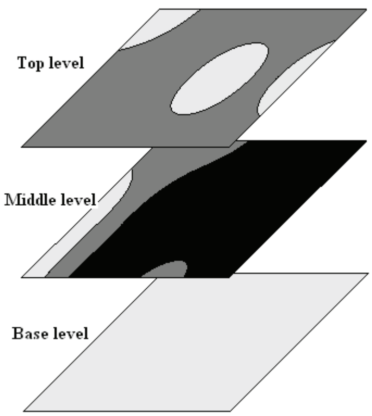


Figure 6- Management zone maps as produced using fuzzy clustering on the three measured parameters for top, middle and base level in empty cold storage for delineation in three zones

Şekil 6- Boş depoda üst, orta ve alt seviyelerde ölçülen üç değer için bulanık mantık kullanılarak oluşturulan yersel değişkenlik haritaları

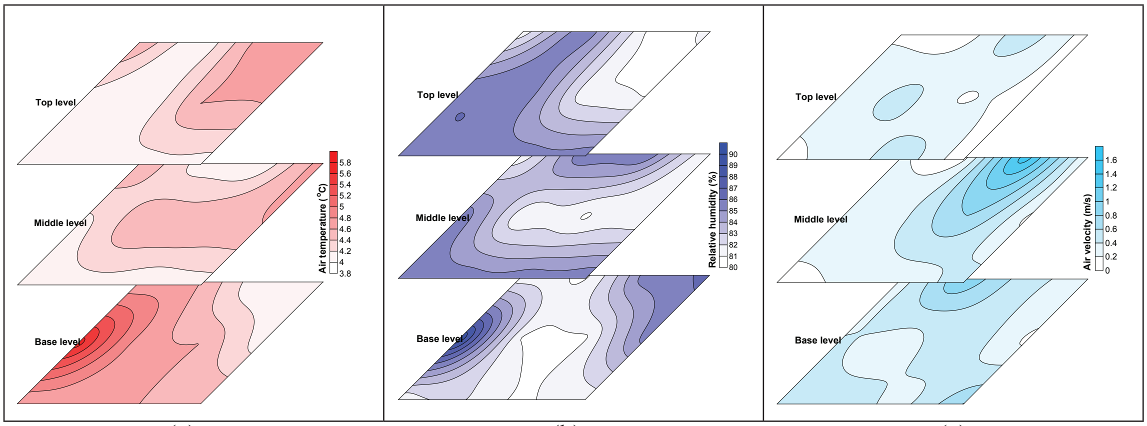
The white zone represents the storage location where storage conditions were excellent showing low temperature (below 3 °C) and high relative humidity (over 90%). In the grey zone the conditions were sufficient presenting low temperature (below 3 C°) and adequate relative humidity (88 – 89.5%). Finally the black zone shows also sufficient storage conditions presenting low temperature (below 3 °C) and adequate relative humidity (87 – 88%). Thus, no action or precaution is needed in empty cold storage.

3.2. Half full cold storage

Figure 7 presents the initial maps for half full cold storage. Air temperature showed intermediate spatial variability in base, middle and top level (C.V. ranged 6.84–9.74%; Table 1). Relative humidity also showed the existence of spatial variation according to descriptive statistics (Table 1) was quite low (the C.V. ranged 2.88–3.64%), if it compares with spatial variability of conventional cold store (Akdemir & Arin 2006).

The maps depicted negative relationship between relative humidity and temperature; areas with higher temperature appeared to show lower relative humidity (Figure 7 a, b). Air velocity showed particularly high spatial variability in the base level (C.V. was 73.44%) and middle level (C.V. was 100%) while in top level spatial variability was significantly lower compared to the other levels but it still was considerably high (C.V. was 51.48%). In half full cold storage, the boxes containing the stored apples were placed on the right part of the storage opposite to the door while the other half of the chamber remained empty (Figure 9). Air velocity was significantly higher in the middle level at the side where the stored apples were settled (Figure 7c). This was probably due to the reduction of the free volume where the air could flow increasing the air velocity. As a result, relative humidity declined at that location leading to increase of temperature.

According to the FPI and NCE indices (Figure 8) the four zones delineation showed minimum values and therefore it was the best option for half full cold storage. Additionally the three zone option was not rejected since it was acceptable option for full cold



(a) (b) (c)

Figure 7- Contour maps of temperature (°C) (a), relative humidity(%) (b) and air velocity (m s^{-1}) (c) for top, middle and base level in half full cold storage

Şekil 7- Yarı dolu soğuk depo içinde üst, orta ve alt seviyeler için sıcaklık (°C) (a) , bağıl nem (%) (b), ve hava hızının (m s^{-1}) (c) kontur haritaları

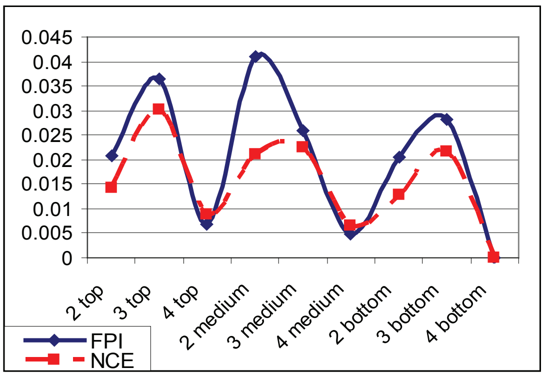


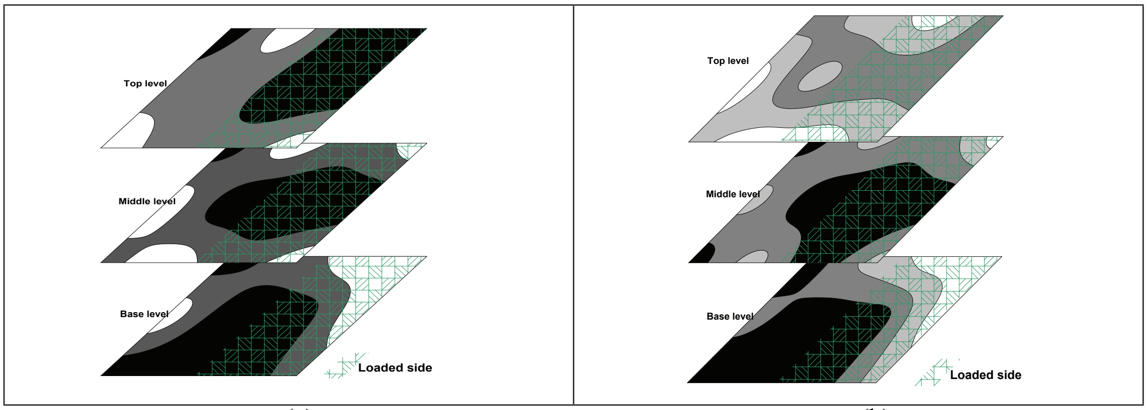
Figure 8- FPI and NCE indices for 2, 3 and 4 zones delineation for the top, middle and base level

Şekil 8- Üst ve orta seviye için 2, 3, ve 4. bölgelerin tanımlanması için FPI ve NCE indisleri

storage and empty cold storage and it was considered interesting to be projected for comparative reasons. Thus the final zone maps delineating three (Figure 9a) and four zones (Figure 9b) were created.

According to the three zone delineation, the empty part of the half loaded cold storage included similar zones for top, middle and base level (Figure 9a). In the four zone delineation, the loaded part of the storage was seperated in two zones at the top and middle level and in three management zones at the base level (Figure 9b). This indicated that there were three different storage conditions for apples stored at base level. Apples may be stored efficiently in storages with temperature between 0 and 2 °C and relative humidity 90-95% (Koyuncu & Eren, 2005). Relative humidity in top and middle level varied between 86% and 90% and it was considerably higher at the unfilled part of the storage in middle and base level because of the insufficient cold air distribution.

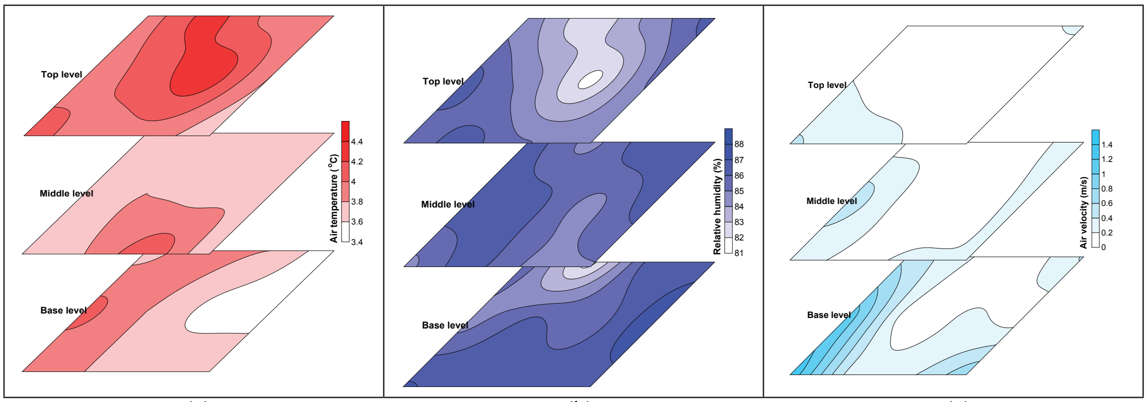
In the zone maps (Figure 9 a and b) the white zone represents the storage location where storage conditions were excellent low temperature (below 4 °C) and high relative humidity (over 90%) are prevailing. The grey zone shows sufficient storage conditions that indicates the intermediate temperature of 3–4.5 °C and relative humidity of 83 – 87%. In top and medium level, the loaded part of storage belonged in the black zone where the ambient conditions are poor and insufficient for apple storage (temperature 4.5 – 5.8 °C and relative humidity 80 – 84%). Apple storage should be avoided in this location for extended time period. Additionally the stored boxes should be positioned in a more sufficient way, leaving gaps between the



(a) (b)

Figure 9- Management zone maps as produced using fuzzy clustering on the three measured parameters for top, middle and base level in half full cold storage for delineation in three (a) and four zones (b)

Şekil 9- Yarı dolu depoda üst, orta ve alt seviyelerde ölçülen üç değer için bulanık mantık kullanılarak oluşturulan yersel değişkenliklerin üç(a) ve dört(b) bölgeli haritaları



(a) (b) (c)

Figure 10 - Contour maps of temperature (°C) (a), relative humidity(%) (b) and air velocity (m s^{-1}) (c) for top, middle and base level in full cold storage

Şekil 10- Dolu soğuk depo içinde üst, orta ve alt seviyeler için sıcaklık (°C) (a) , Bağıl nem (%)(b) , ve hava hızının (m s^{-1}) (c) kontur haritaları

boxes, to enchance the cold air circulation. On the other hand the loaded section in the bottom level was in the white and grey zone indication that the ambient conditions were sufficient.

3.3. Full cold storage

Using the data from full cold storage measurements the initial maps were created (Figure 10). Air temperature showed intermediate spatial variability in base, middle and top level (C.V. ranged 3.46 – 6.06%; Table 1). Relative humidity showed considerably low spatial variability (C.V. ranged 1.2 – 1.93%; Table 1). Additionally, the maps depicted negative relationship between relative humidity and temperature; areas with higher temperature appeared to show lower relative humidity (Figure 10a, b). Air velocity showed particularly high spatial variability in the base level (C.V. was 91.27%) while in middle and top level spatial variability was significantly lower but still considerably high (C.V. was 72.02 and 63.84% respectively).

According to the FPI and NCE indices (Figure 11) the best option for the full cold storage was considered to be the 3 and 4 zone delineation.

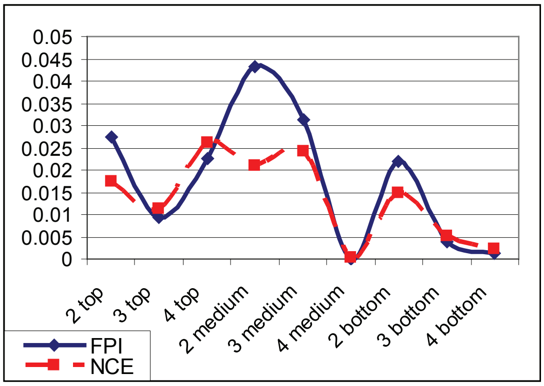
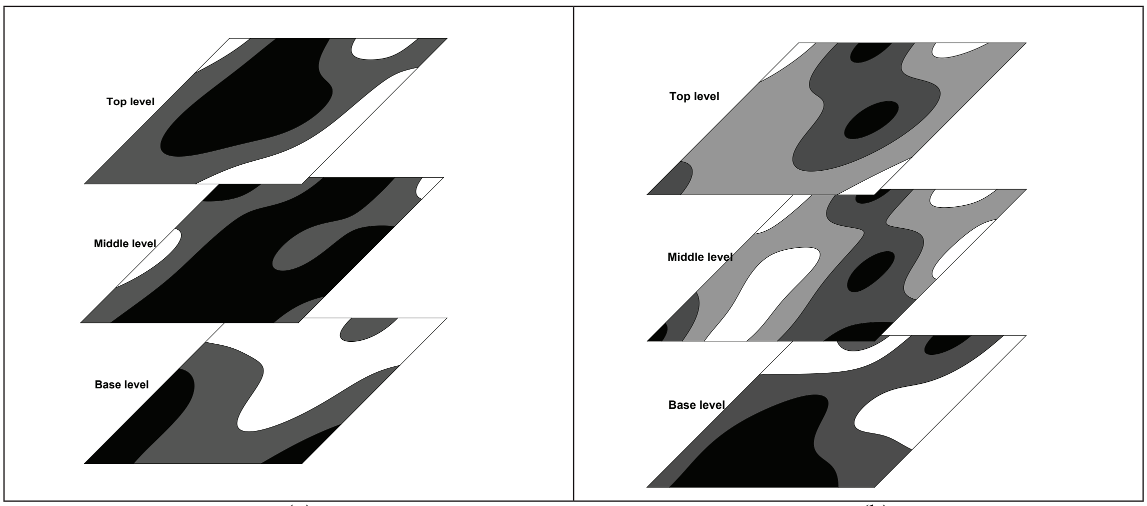


Figure 11- FPI and NCE indices for 2, 3 and 4 zones delineation for the top, medium and base level

Şekil 11- Üst ve orta seviye için 2, 3, ve 4. Bölgelerin tanımlanması için FPI ve NCE indisleri

In the three zones delineation almost total area of base level was classified in the white or grey zone indicating that ambient conditions were satisfactory (Figure 12a). On the other hand the central area in top and middle storage level showed inadequate storage conditions and therefore they were categorized in the black and grey zone. Similar results showed the four zone analysis (Figure 12b). Extra care should be spent for products stored in these zones; frequent inspections and minimization of storage time could be practical and valuable management practices concerning these zones.

Additionally air velocity was minimized in these zones indicating insufficient air circulation (Figure 10c). This was explained by the installation of cold air ventilation inlets which were located on the ceiling of the cold storage (Figure 3). The cold air was inserted though the ventilation inlets on the left, and since it was heavier it flowed straight to the base level. Thus, in the black zone area the stored boxes should be placed in a more sufficient way, leaving larger gaps between them, to enchance the cold air circulation. Another solution could be the



(a) (b)

Figure 12 - Management zone maps as produced using fuzzy clustering on the three measured parameters for top, middle and base level in full cold storage for delineation in three (a) and four zones (b)

Şekil 12- Dolu depoda üst, orta ve alt seviyelerde ölçülen üç değer için bulanık mantık kullanılarak oluşturulan yersel değişkenliklerin üç (a) ve dört (b) bölgeli haritaları installation of extra ventilation inlets and outlets at the side walls of the storage.

The four zone delineation, was proved to be improper for the current study because of the dimensions of the cold storage facility. In such small volume, delinieation in more than 3 zones led to small sized areas which were practically non manageable. The four zone delinieation might be suitable for large commercial cold storages.

4. Conclusions

Spatial variability of ambient factors was significant in cold storage facilities. Using management zone analysis is a novel approach in cold storage management. This approach may be useful to estimate the amount of storage losses and to develop and design possible solutions for better storage efficiency. Amount or percentage of each zone area can be also calculated to quantify the management approaches. These results can be used to find solutions in the most significant cold storage issues; the uneven temperature and relative humidity distribution. For example an additional cold air channel system could be designed to distribute or to flow cold air between the stored boxes. Additionally, a ventilator may be used to establish more homogenous environment in the cold storage. Mapping of the basic storage parameters and zone delineation would be valuable in determining storage conditions of agricultural products. Variation of storage conditions greatly affects quality of stored products. Using sensors in cold storage is an easy and rapid method to attain valuable data and monitor the storage conditions on an ongoing basis. Fuzzy clustering was proved to be a sufficient tool to manage spatial variation of cold storage properties and to delineate zones of differential management. Further investigation should be focused on this subject to include analysis of spatial variation of ambient conditions and spatial variation of stored product quality.

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Abbreviations and Symbols	
FPI	fuzziness performance index
c	number of the cluster
k	indices
i	indices
u_{ik}	membership value to the *i*th cluster centter in the cluster centroid matrix for the *k*th observation in data matrix
n	the number of the observations
H	classification entropy
U	fuzzy membership matrix
a	logarithmic base
NCE	normalized classification entropy
RH	relative humidity
V	air velocity
t	ambient temperature
Std.Dev.	standard deviation
C.V.	coefficient of variation

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