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ARTICLE

Temperature and relative humidity dynamic effect inside a soybean metal silos storage: evidence from Brazil

Efeito dinâmico da temperatura e umidade relativa no armazenamento de soja em silos metálicos: evidências do Brasil

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Abstract: The research main purpose is to realize a short-term forecast temperature values inside metal soybean storage silos using the variables temperature and relative humidity, to predict and analyze the impulse response using vector autoregressions (VAR) with the Seemingly estimator. Unrelated Regression (SUR). The soybean storage silo is considered a multivariate system, as inside the metallic structure there are several temperature and relative humidity sensors, both located internally and externally. As a multivariate system, equations were adjusted using the vector autoregressive methodology, to capture external shocks and their influence on each variable and, determine how long this impact will take effect on the system. The forecast and response impulse show in advance the moment in which that the aeration process must be started. The system of equations points out that the prototype's external variables represented by temperature 7 (T7) and humidity (U7) directly influence other variables. After the occurrence of an external shock, endogenous variables take 4 periods of time to stabilize. An external action, whether naturally or through aeration, will take around eight hours to have an effective change in temperature and humidity. The forecast provides advance knowledge to carry out aeration in the silo, in order to keep the temperature and relative humidity controlled. As 6 periods of time are needed for the response to be carried out, ranging from hours to 12 hours, given that the observations were collected every 2 hours, this time was necessary to stabilize the variables. Keep these variables at target values to add commercial value to the product.

Keywords: soybean, silos, temperature, humidity, autoregressive vectors, dynamic regressions.

Resumo: O principal objetivo desta pesquisa é realizar uma previsão de curto prazo da temperatura dentro de silos metálicos de armazenamento de soja utilizando as variáveis temperatura e a umidade relativa, para prever e analisar o impulse de resposta utilizando vetores autorregressivos (VAR) com o estimador Seemingly Unrelated Regression (SUR). Considera-se o silo de armazenamento de soja como um sistema multivariado, pois dentro da estrutura metálica existem vários sensores de coleta de temperatura e de umidade relativa, localizados tanto interno como externamente. Por ser um sistema multivariado foram ajustadas equações por meio da metodologia de vetores autorregressivos, para captar os choques externos e sua influência em cada variável e determinar quanto tempo de ação deste impacto no sistema. A previsão e o impulso de resposta mostram antecipadamente o momento em que o processo de aeração deve ser iniciado. O sistema de equações aponta que as variáveis externas do protótipo representadas pela temperatura 7 (T7) e umidade (U7) influenciam diretamente outras variáveis. Após a ocorrência de um choque externo, as variáveis endógenas levam 4 períodos de tempo para começarem a se estabilizar. Uma ação externa, seja por via natural ou por aeração, levará cerca de oito horas para que haja uma mudança efetiva de temperatura e umidade. A previsão fornece conhecimento antecipado para realizar a aeração no silo, de forma a manter a temperatura e a umidade relativa controladas. Como são necessários 6 períodos para que a resposta seja realizada, em número de horas a 12 horas, dado que as observações foram coletadas de 2 em 2 horas, esse tempo foi necessário para estabilizar as variáveis. Manter essas variáveis em valores alvo para agregar valor comercial ao produto.

Palavras-chave: soja, silos, temperatura, umidade, vetores autorregressivos, regressões dinâmicas.

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1. INTRODUCTION

The importance of soybean cultivation is a well-documented subject in the literature (Maciel et al., 2015; Pagano & Miransari 2016; Anda et al., 2020), being one of the main sources of protein and vegetable oil in the world (Colombo et al., 2018; Galazzi et al., 2019; Nadeem et al., 2019). Due to its importance to humanity, new research on planting, harvesting and storage may contribute to a better understanding of soybean production in the globally context.

Among the countries with the highest production rate, such as the USA, China, India and Argentina, Brazil has been increasingly prominent on the world stage (Abrhám et al., 2021). In Brazil, soybean was first cultivated at the Agricultural station is Campinas (State of São Paulo) in 1901, and it was officially introduced in Rio Grande do Sul state in 1914. Soybean is one of the main agricultural products produced in Brazil and has positive results in terms of productivity (Empresa Brasileira de Pesquisa Agropecuária, 2014; Loyola et al., 2019).

A surplus in Brazilian trade balance has been presented in the last decades, and the product quality is necessary in order to keep the country's economic growth (Instituto Brasileiro de Geografia e Estatística, 2017; Rodrigues Moreira et al., 2016; Soares et al., 2018; Hong & Huang, 2022). The economic value added to soybean depends on good storage conditions, once the grain is exported, besides being consumed in the domestic market (Poeta et al., 2017; Bellassen et al., 2019; Yadav et al., 2020; Feng et al., 2023). The soybean characteristic quality depend on the storage and the level at which the grain is kept dry, in this context, it is necessary to analyze the behavior of temperature and humidity variables in storage (Empresa Brasileira de Pesquisa Agropecuária, 2014; Martinez-Feria et al., 2019; Vergara et al., 2019; Abati et al., 2022).

Soybean grain moisture variation is very slow in relation to temperature variation and, according to d'Arce (2011), Ziegler et al. (2021), when there is heating inside the silo, internal heat zones are formed due to the fact that the grains have low thermal conductivity.

Temperature control is done by aeration, (a forced passage of air through a mass of ensiled grains) which promotes the stored product. Another important variable to be controlled is the relative humidity, which is not currently been evaluated in the drying and storage process (Krzyzanowski et al., 2006; Kukal & Irmak, 2016; Coradi & Lemes, 2018; Kukal & Irmak, 2018).

Among the main factors affecting soy production, the proper storage is important to maintain the product quality. The wide humidity variation in storage parameters is important to understanding the dynamic of the soybean storage for management purposes of production. Evaluating soy production and storage can improve the effects of different factors affecting soy growth and yield globally (Pagano & Miransari, 2016; Anderson et al., 2019; Zheng et al., 2020).

The research main purpose is to realize a short-term forecast temperature values inside metal soybean storage silos using the variables temperature and relative humidity, to predict and analyze the impulse response using vector autoregressions (VAR) with the Seemingly estimator. Unrelated Regression (SUR). The main contributions are: (i) determine if the causal relationship of temperature and relative humidity inside the soybean metal silos predict values in a short term by means of adjustments and forecasting statistics and (ii) know the temperature and humidity behavior of variables inside the silo, and help the users control these variables to maintain the grain quality storage.

In general, the internal temperature is observed inside the silos during the grain drying process. In this study, to carry out short-term forecast and analyze the variable behavior, internal and external temperatures and relative humidity are captured to compose a short-term forecast model. By checking how the temperature and relative humidity of the environment affect the inside of the silo, which is a novelty in silos, it is possible to take adjustment measures in the drying process in advance.

2. THEORETICAL FOUNDATION

2.1. SOYBEAN STORAGE AND MOISTURE MIGRATION

Storing soybeans is a fundamental step in the production chain, as it enables the preservation and storage of the product after harvest. It is essential to ensure that soybeans are kept under suitable conditions, thereby preventing both quality and quantity losses during storage. Grain storage can be carried out in two ways: in bulk (without packaging) or in containers (sacks). Bulk storage, typically in silos, consists of individualized cells constructed from metal sheets, concrete, or masonry. Key considerations in storage include temperature, humidity, ventilation, pest control, and proper packaging. It is well-known that the moisture content of grains changes much more slowly than temperature, necessitating frequent moisture level analysis (Campanholi et al., 2022; Ding et al., 2019).

One of the most relevant features concerning moisture migration is the moisture gradient within the stored soybean mass, which is the difference in moisture content between the grain's center and its periphery. This gradient is a result of various factors, including temperature and relative humidity differences between the grain's surface and its core. As moisture migrates from the exterior to the interior of the grain, issues such as condensation and the formation of hot spots can arise, potentially leading to the proliferation of microorganisms.

The heating of the stored mass is generated by the respiratory process of moist grains in association with fungi. This heating, caused by these microorganisms, occurs when the moisture content of the grains exceeds the level considered satisfactory for their storage. Respiration and heating in a grain mass are considered together because they are integral components of the same biological process, which leads to the primary deteriorations of the product.

According to d'Arce (2011), when heating is observed in a specific region within a bulk-stored grain mass, it forms what is referred to as a "heat pocket," primarily because a grain mass exhibits low thermal conductivity. The generated heat can accumulate in the region more rapidly than it dissipates, leading to a swift temperature rise in the heated area. This is due to a pronounced acceleration of respiration when both temperature and grain moisture content increase. Heat pockets can also originate from a point of insect infestation.

Muir & White (2000) stated that the optimal temperature range for the development of most microorganisms is between 20 and 40°C. Christensen & Kaufmann (1974) mentioned that relative humidity and temperature are limiting factors for the development of storage fungi. They further asserted that the minimum required relative humidity for the development of Aspergillus Glaucus falls within the temperature range of 26 to 30°C, and its chance of survival is 73%.

Regarding the heat transfer within the grain mass, Smith & Sokhansanj (1990) found that natural convection is not significant for small-sized grains, as in the case of wheat. The dominant heat transfer process within the grain mass is conduction.

To understand and mitigate moisture migration in soybean storage, it is important to consider various related concepts and theories, such as:

Understanding Moisture Equilibrium: Fundamental to determining the equilibrium moisture content of soybeans under different temperature and relative humidity conditions. Knowledge of this equilibrium is essential for defining optimal storage conditions.

Influential Factors: Factors like temperature, relative humidity, grain density, and storage system properties play a crucial role in moisture migration in soybeans.

Mathematical Models: Mathematical models can be used to predict moisture migration within soybean grains, aiding in storage decision-making.

Control Techniques: Techniques for controlling moisture migration during soybean storage, including hydration, cooling, and ventilation systems.

Impact on Grain Quality: Exploring the negative effects of moisture migration on the quality of stored soybeans, including mycotoxin formation, interference with nutritional value, and potential human health risks. The classification degree of soybean storage humidity by Muir & White (2000) is listed in Table 1, and these intervals are the ones that best represent the product quality state when stored in silos.

Table 1 - Inferences of the moisture degree in soybean

Humidity Degree	Inference
humidity< 14%	Dry
14% < humidity > 16%	Not very dry
16% < humidity > 18%	Humid
humidity > 18%	Very humid

Source: Muir & White (2000).

Soybeans are only harvested when the farmer determines that the seed's moisture content falls between 16% and 18% (wet basis). According to Almeida (2016), the optimal moisture content for storing soybeans in silos would be 12% (wet basis) for one year of storage and 11% (wet basis) for five years of storage. Moisture content, or water content, is defined as the product of the water mass contained within the grain (dry matter + water = wet substance). The percentage relationship between the water content and the dry matter of the grain is expressed in terms of wet basis percentage (%wet basis), known as grain moisture, and the moisture inside the silo or prototype is referred to as relative humidity.

Soybean grains are considered hygroscopic materials, which means they have the capacity to release or absorb moisture from the surrounding air. For each type of grain, there exists a hygroscopic equilibrium, which is essentially a balance between the grain's moisture content and the relative humidity of the air. Examining the information in Table 2, we obtain a reference for soybean grain moisture concerning the relative humidity of the air and the temperature in degrees Celsius.

Table 2 - Moisture content of soybean grains at different relative humidity levels and temperatures

Relative humidity (%)	Air temperature (°C)								
	8°C	14°C	20°C	22°C	25°C	28°C	31°C	33°C	36°C
	Internal seed moisture (%)								
30%	9.2	8.2	7.2	6.7	6.2	5.7	5.2	4.7	4.2
35%	9.6	8.6	7.6	7.1	6.6	6.1	5.6	5.1	4.6
40%	10	9	8	7.5	7	6.5	6	5.5	5
45%	10.4	9.4	8.4	7.9	7.4	6.9	6.4	5.9	5.4
50%	11.1	10.1	9.1	8.6	8.1	7.6	7.1	6.6	6.1
55%	11.9	10.9	9.9	9.4	8.9	8.4	7.9	7.4	6.9
60%	12.7	11.7	10.7	10.2	9.7	9.2	8.7	8.2	7.7
65%	13.9	12.9	11.9	11.4	10.9	10.4	9.9	9.4	8.9
70%	15.1	14.1	13.1	12.6	12.1	11.6	11.1	10.6	10.1
75%	16.2	15.2	14.2	13.7	13.2	12.7	12.2	11.7	11.2
80%	17.4	16.4	15.4	14.9	14.4	13.9	13.4	12.9	12.4

Source: Almeida (2016)

According to Table 2, there is an increase in the seed's internal moisture when there is a change in relative humidity of the air. These tests conducted by Almeida (2016) highlight the significance of the variable relative humidity of the air in the internal moisture of soybeans, which directly impacts the quality of the stored product.

The majority of agricultural cooperatives plan for storage periods of up to one year, as the soybean market is lucrative and in high demand (Gresele, 2020; Manfroi, 2021) During this period, the moisture content of soybean grains should remain at or below 12% (wet basis). To achieve the optimal grain moisture content, as indicated in Table 2, it is necessary to control the variables of relative humidity of the air and temperature. At a relative humidity (RH) of 65% and a temperature of 20°C, the grain moisture content is 11.9%, very close to the ideal value (Almeida, 2016).

2.2. AERATION

The control of temperature and relative humidity of the air is achieved through aeration, which involves the forced passage of air through a stored grain mass, promoting the drying of the stored product (Navarro & Navarro, 2020; Ziegler et al., 2021; Lopes & Steidle Neto, 2022).

In aeration, the grains remain stored in the silo, and it's the air that moves through the seeds. Transilagem, another drying method, has become less common due to its disadvantages compared to aeration. One major drawback is its high cost, as it requires empty silos to move the grains, resulting in a high rate of breakage and damage to the seed coat (the outer covering of the seeds). During the process, there is a short period of exposure of the grains to the air, and several repetitions of this procedure are needed to achieve the desired aeration, making the process costly (Friedmann & Maier, 2020; Navarro & Navarro, 2020).

Aeration is widely adopted in most silos in temperate climate countries. In Brazil, especially in the southern region, including the state of São Paulo, conditions are favorable for using aeration because of the availability of cold air. In tropical regions where obtaining cold air is not possible, aeration should be used with caution. In some cases, negative results may be obtained, such as over-drying of the grain mass if the relative humidity of the air is low, or condensation if the relative humidity is high and the ambient temperature is low. Studies have been conducted in hot climate countries like Australia and Israel, and the benefits of aeration have been widely observed in practice (Puzzi, 2000).

To carry out aeration, one must determine its purpose: drying, storage, temperature maintenance, and/or humidity control (Ziegler et al., 2021). In essence, aeration depends on the grain's temperature and humidity, the ambient air's temperature and relative humidity, and should be supervised by an operator who needs to know, in the hours following the initiation of the process, the required temperature and relative humidity for using the aerator (Aby & Maier, 2020; Ziegler et al., 2021).

According to Bilobrovec (2005), for controlling the temperature of the grain mass, thermometry installations are employed, consisting of a network of temperature sensors arranged regularly within the storage cells of the silos.

Möhler (2010) emphasizes that the drying of soybeans is a process requiring particular care. Given its high protein content and economic value, improper drying can lead to the degradation of this compound. During drying at 120°C, a distinctive burning odor is observed, and by the end of the process, there is a change in the grain's color from the initial yellow to brown.

The temperature within the grain mass is affected by external sources of heat (direct solar radiation, diffuse radiation, and heat transfer through convection with the surrounding air) and internal sources, including heat generated by the respiration of the grain, insects, mites, and fungi (Jia et al., 2000).

The composition and structural characteristics of stored grains vary based on post-harvest operational conditions and are exposed to physical factors such as temperature and humidity, as well as chemical factors like oxygen, carbon dioxide, and biological agents such as bacteria, fungi, insects, and rodents (Elias, 2002).

Gungadurdoss (2003), in a study examining the viability of soybean seeds under different storage conditions, concluded that temperature is the predominant factor in maintaining the viability of soybean seeds.

According to Abba & Lovato (1999), grain storage in natural environments in tropical regions poses greater challenges due to temperature and relative humidity conditions when compared to temperate or cold climate regions.

In tropical regions like Brazil, where storage room temperatures often exceed 20°C, the decline in both vigor and germination percentage is more pronounced (Dhingra et al., 2001).

Burris (1980) suggests that the rapid deterioration of soybeans during storage is influenced by the moisture content and temperature in the stored grain. The process for obtaining soybean grain moisture data is determined using a specific device that measures moisture in the grain mass in percentage units (wet basis). To collect the variables, a software developed for recording temperature and relative humidity of the air is employed.

3. METHODOLOGY

To achieve the main purpose a silo prototype, which has sensors to collect temperature and humidity data is set. Sensors are set inside and outside the silo. Data collection occurred from July 2016 to December 2016, at every two hours, resulting in 954 observations. This period was strategically planned with the aim of capturing information within a timeframe that encompassed various conditions and relevant events for the research in question. Representative Sampling: By extending the data collection period, it was possible to obtain a representative sample of the variable under study. This reduces the possibility of seasonal biases or atypical events disproportionately affecting the results. Long-term Data Collection was essential to capture trends over time. The period allowed identify patterns and changes that may not have been visible in shorter period of time. The sample period data is from July 2016 to December 2016 collected to every two hours. capture all characteristic in the data. This approach contributes to the validity and robustness of the results obtained in the research.

The sensors are used to record the temperatures and humidity, as well as their respective storage over time. The silo prototype is equipped with seven sensors, controlled by specific software and hardware, with the capacity to create and store a database that allows the variables behaviour study in product storage.

The silo prototype was constructed with a 2 mm thickness stainless steel plate in a cylindrical shape, 130 cm high and 80 cm diameter, on an approximate scale of 1:25 of the original size. It was placed outdoors so that variations in temperature and humidity could interfere as it would in a real silo. The prototype was installed in the city of Santa Rosa, RS, in the courtyard of the Educational Foundation Machado de Assis, with the following geographic coordinates: -27.869548, -54.478093.

The proposed architecture is an Arduino board with dht 22 sensors, which can capture the temperature and the air relative humidity. The data are processed by a microcontroller and stored in the operating system.

The vector autoregressive -VAR models is fit to capture the casual relationship among the variables and enable the accomplishment of impulse response function to analyze the behavior of variables over time. After this, a dynamic equation is estimated to forecast temperature and humidity values in a short term (Granger, 2004).

Initially, a descriptive analysis was performed in the morning, afternoon and evening to identify if there were significant differences among the average in the turns. To fit the VAR (p) model, variables must be classified in endogenous and exogenous and set as Equation 1.

$$Yt = A1Yt-1 + A2Yt-2 + \ldots + ApYt-p + B\mathbf{X}t + \varepsilon t \quad (1)$$

Where:

$\boldsymbol{Y}_t$ is a vector of endogenous variables at time *t*.

• $A_1, A_2, \ldots, A_p$ are matrices of autoregressive coefficients that describe how endogenous variables depend on their own past values.

• *p* is the order of the model, determining how many past lags are included.

• $\boldsymbol{X}_t$ is a vector of exogenous variables at time *t* that can affect the endogenous variables.

• ε_t is a vector of errors, assumed to be white noise, i.e., having zero mean, finite covariance, and no autocorrelation.

Adjusted model quality was based on the penalty criteria AIC and BIC, in Equations 2 and 3:

$$AIC = 2k - 2ln(L) \quad (2)$$

$$BIC = k\ ln(n) - 2ln(L) \quad (3)$$

where:

• *k* is the number of parameters in the model (including autoregressive coefficients and error terms).

• *n* is the number of observations in the data.

• ln(*L*) is the logarithm of the likelihood function of the model.

To establish the VAR model the stationary assumption must be achieved and it is verified by Dickey & Fuller (1979, 1981), Kwiatkowski et al. (1992) tests, Silva et al. (2011) and Enders (1995).

After that the lagged number of variables to be included in the model of each endogenous variables is determined by Lag Order Criteria (Ueda et al., 2020), which uses the Akaike information Criteria (AIC) and Bayesian Information Criteria (BIC), the model selected is the one that presents the lowest values to AIC and BIC (Ziegler et al., 2022).

Granger Causality/Block Exogeneity test, was used to order the endogenous variables inside the silos, to compose the VAR model (Charemza & Deadman, 1997). Silo external variables, temperature and humidity are considered exogenous in VAR methodology.

The purpose to fit a VAR(p) model, is that it enables the establishment of the impact of one variable on the others by means of impulse response method, using Cholesky decomposition. Effects are evaluating in terms of standard deviations when a shock is applied to the exogenous variables and transmitted throughout the system (Granger, 2004).

And, finally to get the best forecast values for temperature and humidity from the sensor inside the silo, a dynamic equation is fit, using the lagged variables and the number of lags defined in the established VAR model. Seemingly uncorrelated regressions (SUR) methodology, is used to estimate the parameters, the reason to use SUR by means of Three-Stage Least Square estimation is to keep, in all equations, just the variables statistically significant and, provided an accurate 6-step-ahead-forecast.

4. RESULTS AND DISCUSSION

Data collected by sensors every two hours, from July 2016 to December 2016, are represented in the Figure 1 prototype. Software was developed in Java language; it stores the data and calculates the average temperature and relative humidity to each sensor.

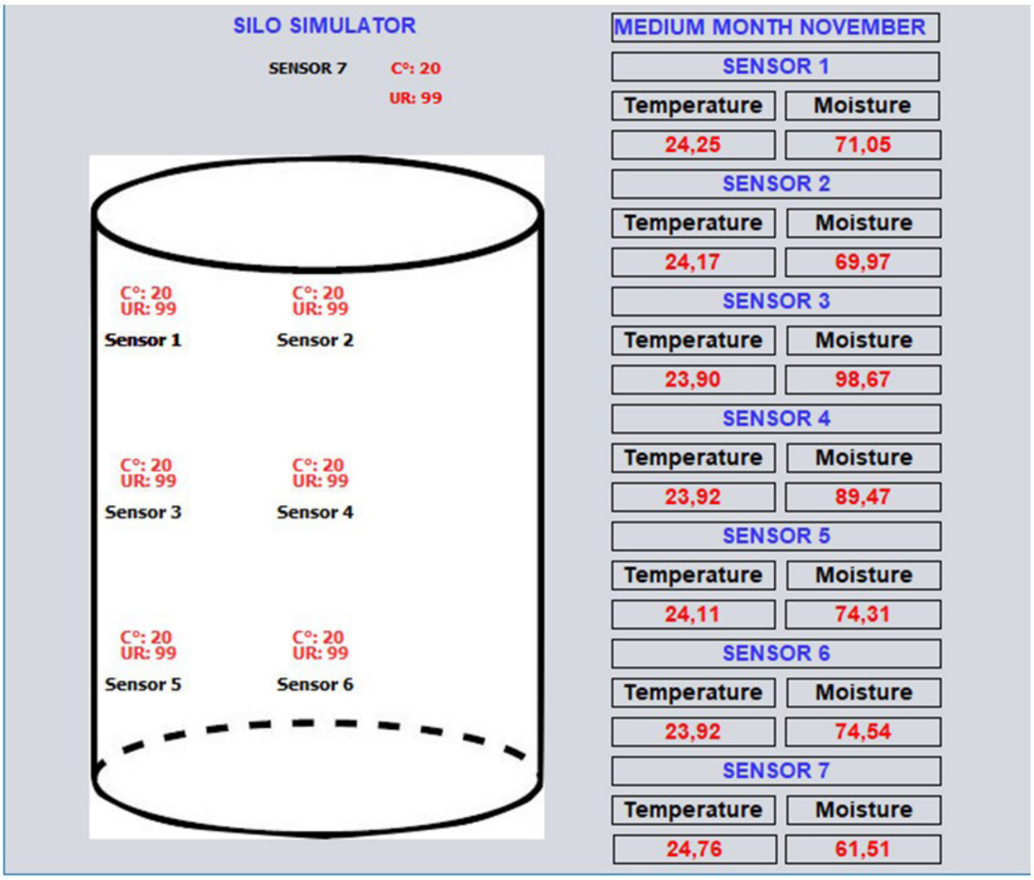

Figure 1 - Silo Prototype with the sensors programmed to individually capture the relative humidity and temperature of each site of the silo prototype, with their respective temperatures and average humidity.
Source: Prepared by the Authors

Variables from sensors 1 to 6, to temperature and humidity are used as endogenous variables. Sensor 7, captures temperature and relative humidity from outside the storage environment as a way to verify the influence to the variables inside the silo, as studied by Palaparthy et al. (2017).

The mean, standard deviation and coefficient of variation of the prototype internal variables are shown in Table 3.

Table 3 - Analyzing all silo prototype internal variables in the storage stage

Variable	Mean	Standard deviation	CV(%)	n
Temperature	21.94°C	2.53	11.55	954
Relative humidity	76.13	7.58	9.95	954

CV: Pearson coefficient of variation, n: number of observations.
Source: Prepared by the Authors

Analyzing Table 3, it is noted that the prototype average temperature is 21.94°. Temperature ranges from of 19.41°C to 24.47°C, outside the ideal range storage value. Mean humidity is high (76.13) relative humidity variation range is from 68.55% to 83.71%, and the product loses its commercial value.

A monthly sudden change was noticed in the study regarding the variable climatic oscillations. The variation coefficient of is below 12% in both variables, which shows a representative average. An increase of the average temperature from 18.48°C to 25.33°C was observed from July, 2016 to December, 2016. Analysis of the variance (ANOVA) test in temperature in relation to the months of year was statistically significant, showing that there are climatic oscillations considering the months. The same analysis was performed in relation to humidity; ANOVA test was not significant, showing that there was no meaningful change of this variable over time.

The variables located in the middle and bottom of the prototype had increased humidity with increasing temperature, and the top variables did not show any increase in humidity, since there is little variation between the months. Analyzing variables U6, U4, U5, U1, U2, U3, T6, T4, T2, T5, T3, it was found that they have a coefficient of variation below 15% over the months, which is classified as low dispersion, and the data are considered homogeneous. To evaluate the variables stationary, ADF test was performed and displayed at Table 4.

Table 4 - Augmented Dickey-Fuller (ADF) unit root test for temperature and humidity variables in level and first differences

ADF	Serie in level			Serie in first difference		
	t-statistic	ADF critical value 5%	*p-value*	t-statistic	ADF critical value 5%	*p-value*
T1*	-4,9364	-2,8644	0,0000	-	-	-
T2*	-3,9316	-2,8644	0,0019	-	-	-
T3*	-4,6545	-2,8644	0,0001	-	-	-
T4	-2,2308	-2,8643	0,1955	-31,0337	-2,8643	0,0000
T5*	-4,3369	-2,8644	0,0004	-	-	-
T6	-2,3214	-2,8643	0,1654	-30,8313	-2,8643	0,0000
T7*	-4,6669	-2,8643	0,0001	-	-	-
U1*	-3,2393	-2,8644	0,0181	-	-	-
U2*	-3,8302	-2,8644	0,0027	-	-	-
U3	1,7372	-2,8643	0,9997	-10,8947	-2,8643	0,0000
U4	0,9830	-2,8643	0,9965	-35,5626	-2,8643	0,0000
U5*	-4,6646	-2,8643	0,0001	-	-	-
U6*	-5,7990	-2,8643	0,0000	-	-	-
U7*	-3,8595	-2,8643	0,0025	-	-	-

*Stationary series in level, one-sided p-values, (T1: temperature sensor 1, T2: temperature sensor 2, T3: temperature sensor 3, T4: temperature sensor 4, T5: temperature sensor 5, T6: temperature sensor 6, T7: Temperature sensor 7, U1: Humidity sensor 1, U2: Humidity sensor 2, U3: Humidity sensor 3, U4: Humidity sensor 4, U5: Humidity sensor 5, U6: Humidity sensor 6, U7: Humidity sensor 7).
Source: Prepared by the Authors

When performing the ADF test, the variables T1, T2, T3, T5, T7, U1, U2, U5, U6 and U7 were stationary in level. The other variables, T4, T6, ΔU3 and U4, were classified as non-stationary in level, therefore they needed a simple difference to reach stationary, so these variables were considered I(1) to compose VAR model. In Table 5, KPSS test is shown used to corroborate results from the ADF test.

Table 5 - Stationarity test Kwiatkowski, Phillips, Schmidt and Shin (KPSS)

KPSS	Series in level		Series in first differences	
	LM-stat	KPSS critical value 5%	LM-stat	KPSS critical value 5%
T1	1,0010	0,4630	0,0619	0,4630
T2	1,2646	0,4630	0,0360	0,4630
T3	1,0673	0,4630	0,0524	0,4630
T4	1,5111	0,4630	0,0341	0,4630
T5	1,2106	0,4630	0,0330	0,4630
T6	1,5029	0,4630	0,0323	0,4630
T7	1,3939	0,4630	0,2216	0,4630
U1	2,6335	0,4630	0,1361	0,4630
U2	2,8113	0,4630	0,0791	0,4630
U3	2,8054	0,4630	0,3643	0,4630
U4	3,2739	0,4630	0,3313	0,4630
U5	3,1807	0,4630	0,2300	0,4630
U6	1,9481	0,4630	0,1102	0,4630
U7	0,5028	0,4630	0,1434	0,4630

Kwiatkowski et al. (1992; Table 1).
Source: Prepared by the Authors

According to KPSS test results, all series T1, T2, T3, T4, T5, T6, T7, U1, U2, U3, U4, U5, U6 and U7 are non-stationary, becoming stationary in first difference, that is I(1). KPSS test showed contradiction with the ADF test, therefore, the choice was to use all variables in first differences to guarantee the stability of the estimated parameters.

A generic VAR is fit considering the variables stationary, this first auxiliar VAR fit model is used to define the lags number to be included in the model. The Lag Order Selection Criteria, must show the lowest values to AIC = 23. 44969 considering the model with 7 lags, it is VAR (7). The lowest to BIC = 25.79289, considering a model with 1 lag, it is VAR (1). As the BIC criteria is used for large samples, but to consider a more parsimonious model, thus, the VAR (1) model was preferred. All endogenous variables show 1 lag.

The order of variables in relation to their degree of erogeneity, given by the Block Exogenety test, is: Δ(U1), Δ(T3), Δ(T2), Δ(T1), Δ(U7), Δ(T7), Δ(U2), Δ(U5), Δ(U3), Δ(U6), Δ(U4), Δ(T6), Δ(U5), Δ(T4), all variables in first differences.

Considering that the system is composed by prototype internal temperatures and relative humidity, the variables in first differences, Δ(T7) and Δ(U7) are considered exogenous, which represent environment oscillations and are measured by the prototype external sensor. The structural VAR model captures interrelationships and is useful for performing the impulse responses. In order to capture the effect that one variable causes in others, the estimated equations are used, and a response impulse is made, as shown in Figure 2.

According to Figure 2, when an external shock of one a standard deviation is applied in variable temperature Δ(T7), the response at temperatures Δ(T3), Δ(T2), Δ(T1), Δ(T5) and humidity Δ(U4) occurs. There is also an increase until the second period, falling in period three and stabilizing until the sixth period. The variables Δ(U1), Δ(U3), Δ(U2), Δ(U5) and Δ(U6) show a decrease until period two they, increase until the third period and they stabilize until the sixth period. The variables Δ(T6) and Δ(T4) show a decreasing response until the fourth period and, afterwards, they stabilize in the sixth period.

Impulse performed on the variable D(U7) and responses on other endogenous variables, according to Figure 3.

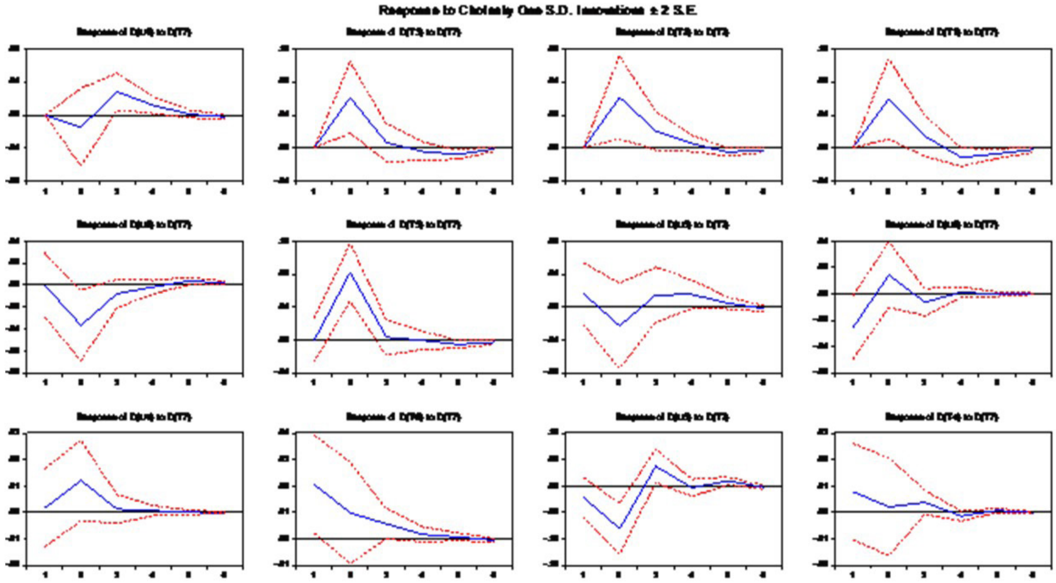

Figure 2 - Impulse performed on T7 variable and responses on the other variables that compose the prototype sensor system.
Source: Prepared by the Authors

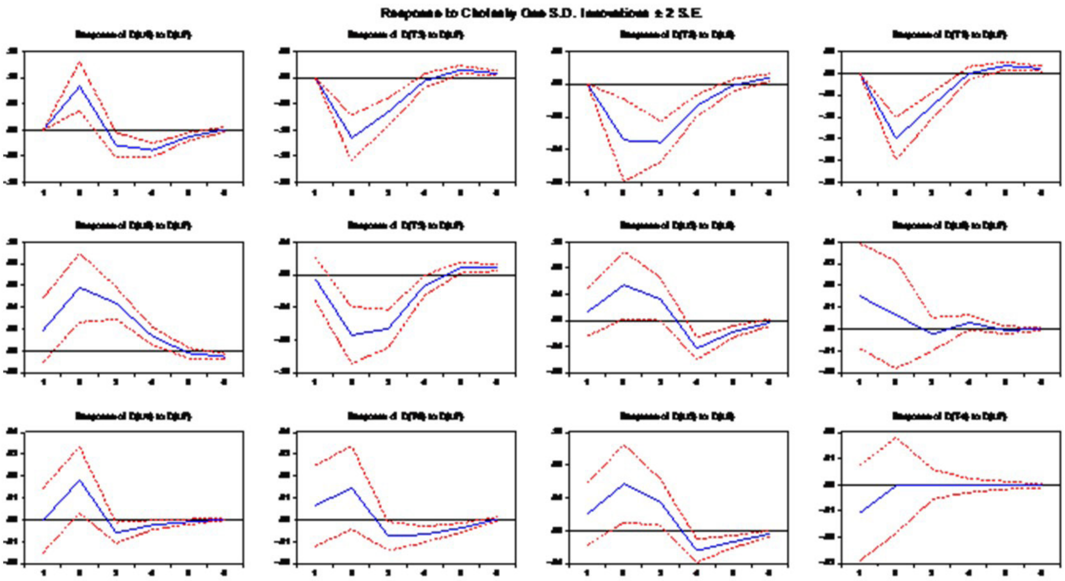

Figure 3 - Impulse performed on variable U7 and responses on the other variables that compose the prototype sensor system.
Source: Prepared by the Authors

According to Figure 3, when an external shock occurs in terms of a standard deviation in variable Δ(U7), humidity Δ(U1) responds with an increase until the second period, falling again until the fourth period and stabilizing until the sixth period. In general, variables Δ(T6), Δ(U3) and Δ(U5) present a response with the same growth, fall and stabilization behavior. On the other hand, variables Δ(T3), Δ(T5), Δ(T2), Δ(T1) respond with an inverse behavior, decreasing until the second period and then rising again to stabilize in the sixth period. Humidity variable Δ(U2) shows an increase response until the second period and, afterwards, decreases until it stabilizes in the sixth period; humidity variable Δ(U4) increases until the second period, falling back to the third period and then stabilizing in the sixth period. Temperature variable Δ(T4) responds with an increase until period two, in which stabilizes. Humidity variable Δ(U6) decreases until the third period and stabilizes. Impulse Response analysis is important because it gives the operator the opportunity to verify what happens to internal variables in the silo when there is an impact on one of the external variables.

Given the interrelationship among them and the way they transmit their effect within the silo, it is necessary to perform a prediction of these variables so that the operator can take an anticipated corrective action, based on the predicted values, keeping maintaining the ideal product temperature and humidity to an acceptable quality.

On the other hand, it keeps some structure non-significant variables, which do not provide good model for forecasting. In order to know the variables future behavior 6 six periods ahead, a joint estimation is made by means of dynamic equations, using Three-Stage estimator which is adequate to equations with characteristics of Seemingly Unrelated Regression. The estimated dynamic equation models present residues with white noise characteristics, and all the estimated parameters are significant, with the lowest values to adjustment AIC = -21.6854 and BIC = - 21.3974.

The predicted values in horizon of a 6-step ahead, estimated by the dynamic models, are in Table 6. The forecast horizon corresponds to twelve hours of work, enough time for a decision making regarding the studied variables calibration.

After values are forecasted, it is possible for the operator to know the future behaviour of each variable in order to keep the temperature and relative humidity close to its established target values to maintain the stored product quality of the product stored.

Dynamic modelling equations allowed to determine which sensors or prototype place are determinant for these variables control Variables manipulation involved in the study to keep maintain their ideal values is done by silo aeration, which is equipped with fans that perform this process. The time each point of the silo takes to receive a pulse, represented by lags, Will be an aid for this task.

Table 6 - Predicted values for the prototype internal variables, with a horizon of h = 6 steps forward

Forecast for variable T1						Equation for U1					
h	**Date**	**Time**	**Forecast**	**Real**	**Standard error**	**h**	**Date**	**Time**	**Forecast**	**Real**	**Standard error**
955	20/10/16	22:00:00	235,039	24	0,7384	955	20/10/16	22:00:00	719,105	72	0,7250
956	21/10/16	00:00:00	231,668	24	11,880	956	21/10/16	00:00:00	719,302	72	0,9694
957	21/10/16	02:00:00	229,282	23	15,840	957	21/10/16	02:00:00	719,708	72	11,200
958	21/10/16	04:00:00	227,104	23	19,590	958	21/10/16	04:00:00	720,134	72	12,180
959	21/10/16	06:00:00	225,141	22	23,300	959	21/10/16	06:00:00	720,428	72	12,920
960	21/10/16	08:00:00	223,338	22	26,960	960	21/10/16	08:00:00	720,603	71	13,540
Forecast for variable T2						**Equation for U2**					
h	**Date**	**Time**	**Forecast**	**Real**	**Standard error**	**h**	**Date**	**Time**	**Forecast**	**Real**	**Standard error**
955	20/10/16	22:00:00	245,229	24	0,3459	955	20/10/16	22:00:00	702,700	70	0,4687
956	21/10/16	00:00:00	241,785	24	0,4792	956	21/10/16	00:00:00	704,913	70	0,6738
957	21/10/16	02:00:00	239,288	24	0,6382	957	21/10/16	02:00:00	706,900	71	0,8777
958	21/10/16	04:00:00	237,372	24	0,8261	958	21/10/16	04:00:00	708,723	71	10,840
959	21/10/16	06:00:00	235,729	24	10,330	959	21/10/16	06:00:00	710,468	72	12,910
960	21/10/16	08:00:00	234,231	23	12,520	960	21/10/16	08:00:00	712,123	72	14,970

h: forecast horizon.
Source: Prepared by the Authors

Table 6 - Continued...

Forecast for variable T3						Equation for U3					
h	Date	Time	Forecast	Real	Standard error	h	Date	Time	Forecast	Real	Standard error
955	20/10/16	22:00:00	235.587	24	0.6169	955	20/10/16	22:00:00	965.133	96	0,759
956	21/10/16	00:00:00	232.185	24	0.9416	956	21/10/16	00:00:00	966.652	96	1,059
957	21/10/16	02:00:00	229.943	23	12.540	957	21/10/16	02:00:00	968.570	96	1,248
958	21/10/16	04:00:00	227.848	23	15.560	958	21/10/16	04:00:00	970.016	96	1,386
959	21/10/16	06:00:00	226.027	23	18.600	959	21/10/16	06:00:00	971.444	96	1,489
960	21/10/16	08:00:00	224.313	22	21.650	960	21/10/16	08:00:00	972.701	96	1,569
Forecast for variable T4						Equation for U4					
h	Date	Time	Forecast	Real	standard error	h	Date	Time	Forecast	Real	standard error
955	20/10/16	22:00:00	241.329	24	0.2726	955	20/10/16	22:00:00	860.381	86	0.2326
956	21/10/16	00:00:00	242.094	24	0.3735	956	21/10/16	00:00:00	860.564	86	0.3077
957	21/10/16	02:00:00	242.462	24	0.4456	957	21/10/16	02:00:00	860.747	86	0.3716
958	21/10/16	04:00:00	242.559	24	0.5022	958	21/10/16	04:00:00	860.910	86	0.4282
959	21/10/16	06:00:00	242.476	24	0.5500	959	21/10/16	06:00:00	861.057	86	0.4813
960	21/10/16	08:00:00	242.257	24	0.5933	960	21/10/16	08:00:00	861.188	86	0.5330
Forecast for variable T5						Equation for U5					
h	Date	Time	Forecast	Real	standard error	h	Date	Time	Forecast	Real	standard error
955	20/10/16	22:00:00	241.681	24	0.468	955	20/10/16	22:00:00	745,737	75	0.6444
956	21/10/16	00:00:00	238.008	24	0.736	956	21/10/16	00:00:00	746,870	75	0.8099
957	21/10/16	02:00:00	235.390	24	0.999	957	21/10/16	02:00:00	746,824	75	0.9033
958	21/10/16	04:00:00	233.256	23	1.270	958	21/10/16	04:00:00	746,660	75	0.9706
959	21/10/16	06:00:00	231.393	23	1.549	959	21/10/16	06:00:00	746,567	75	10.250
960	21/10/16	08:00:00	229.681	23	1.834	960	21/10/16	08:00:00	746,517	75	10.710
Forecast for variable T6						Equation for U6					
h	Date	Time	Forecast	Real	standard error	h	Date	Time	Forecast	Real	standard error
955	20/10/16	22:00:00	241,114	24	0,2762	955	20/10/16	22:00:00	739,602	74	0,3722
956	21/10/16	00:00:00	241,557	24	0,3688	956	21/10/16	00:00:00	739,350	75	0,4622
957	21/10/16	02:00:00	241,285	24	0,4428	957	21/10/16	02:00:00	739,101	75	0,5476
958	21/10/16	04:00:00	240,590	24	0,5210	958	21/10/16	04:00:00	738,887	75	0,6170
959	21/10/16	06:00:00	239,650	24	0,6144	959	21/10/16	06:00:00	738,696	75	0,6786
960	21/10/16	08:00:00	238,570	24	0,7278	960	21/10/16	08:00:00	738,530	75	0,7339
Forecast for variable T7						Equation for U7					
h	Date	Time	Forecast	Real	Standard error	h	Date	Time	Forecast	Real	standard error
955	20/10/16	22:00:00	226,597	22	3,463	955	20/10/16	22:00:00	653,471	68	9,883
956	21/10/16	00:00:00	224,850	21	5,033	956	21/10/16	00:00:00	653,914	74	14,44
957	21/10/16	02:00:00	223,217	19	6,210	957	21/10/16	02:00:00	654,160	81	17,90
958	21/10/16	04:00:00	221,602	19	7,185	958	21/10/16	04:00:00	654,392	86	20,79
959	21/10/16	06:00:00	219,999	18	8,031	959	21/10/16	06:00:00	654,625	89	23,33
960	21/10/16	08:00:00	218,407	19	8,785	960	21/10/16	08:00:00	654,857	85	25,62

h: forecast horizon.
Source: Prepared by the Authors

5. CONCLUSIONS

The research realize a short-term forecast temperature values inside metal soybean storage silos using the variables temperature and relative humidity. The inclusion of variable relative humidity enable the model capture the dynamic among the variables, and select the variable with major impact. The causal relationship of temperature and relative humidity inside the soybean metal silos improve it's predicted values in a short term and to know the temperature and humidity behavior of variables inside the silo, and help the users control these variables to maintain the grain quality storage.

The prototype allowed to collect the relative air temperatures and humidities simultaneously. Considering that the current silos only work with temperature measurements, the humidity enables to evaluate the process accurately, providing the interrelationship understanding among the variables. The VAR (1) model shows that just 1 period of time is important to capture the effect among the endogenous variables.

External variables such as temperature and humidity affect the endogenous variables inside the silo, and silo top variables have causal relation with themselves and in the others. Analyzed variables are interdependent in relation to their location in the silo, which is proven by the positioning of the sensors reflected in the estimated equations coefficients.

It was observed that an external shock when performed on the exogenous variables, sensor 7, which represent the environment, has an effect in endogenous variables. External temperature and relative humidity changes directly influenced internal temperature and humidity.

Collect one-year storage silos or more is required to monitor carefully the operator's performance, considering that periods of cold, frost, drought and rainfall will interfere with internal storage conditions. In order to obtain assertive predictions, the dynamic equations allowed that only the significant variables remained in the model, which is an advantage in relation to structural VAR model.

Forecast provides anticipated knowledge to perform the aeration in the silo, in order to maintain the temperature and relative humidity controlled. As it takes a response 6 periods that correspond to 12 hours, this will the time needed to stabilize the variables. Based on the temperature and humidity behavior it is important to establish a controller to maintain these variables at target values in order to add commercial value to the product.

It is important to highlight some specifications that may impact the validity and results generalizability. The results validity can be affected by the sensor's accuracy used for collecting the variables measurements. Errors or imprecisions in the input data can introduce bias into the models and, consequently, affect the conclusion regarding the causal relationship. The results obtained may be specific to the prototype of the constructed soybean storage silo and the experimental conditions used. Generalizing to other types of silos or conditions may not be straightforward. Simplicity of the prototype, the constructed prototype may not fully capture the complexity and real variation present in soybean storage silos. Duration and scope of the study may have a limited duration or cover a specific period. Seasonal changes, yearly variations, or extreme events may not be fully considered, potentially limiting the applicability of the results in the long term. Data availability, the limited availability of historical data or the quality of the data can affect the robustness and reliability of the analyses, especially concerning time series models.

It is essential to consider and discuss these limitations to ensure an appropriate interpretation of the results and enable future improvements in the study and related research.

Based on this study, several suggestions can be made to guide future research in the same area or related to similar analyses of soybean storage silos. Some suggestions include incorporating more variables, considering the inclusion of additional relevant variables such as atmospheric pressure, wind, and soybean grain characteristics. This can provide a more comprehensive understanding of the factors that affect the internal environment of the silos. Evaluating other types of statistical models, machine learning models, or hybrid models to predict and understand the relationship between temperature, relative humidity, and the behavior of storage silos. Conducting real-scale studies in operational soybean storage silos. Long-term assessment, extending the study duration to evaluate the behavior of variables over a more extended period, encompassing different seasonalities and weather conditions. Sensitivity and robustness analysis, performing sensitivity analyses to assess how small variations in parameters and observed initial conditions affect the outcomes. Additionally, leveraging the robustness of the models in different contexts. Exploring an integration of optimization techniques to enhance the operational efficiency of storage silos, considering the relationship between temperature, relative humidity, and other factors. Assessing the impact of internal silo conditions, influenced by temperature and humidity, on energy efficiency and operational costs. This can help optimize silo management. Expanding the study to include different types of grains stored in silos, beyond soybeans, to understand variations in the relationships among temperature, humidity, and storage behavior. Integrating emerging technologies, such as the Internet of Things and Artificial Intelligence, to improve data collection and real-time decision-making processes. Conducting additional experiments to validate the results obtained through simulations and models, providing a more solid foundation for the study's conclusions. These suggestions aim to expand knowledge in the grain storage field and can contribute to improvements in silo management practices, enhancing operational efficiency, and reducing losses.

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