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USING THE DIMENSIONAL ANALYSIS FOR A MATHEMATICAL MODEL TO PREDICT THE SEEDS LOSSES AT THE CLEANING SYSTEM OF THE CEREALS HARVESTING COMBINES

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În această lucrare se abordează, pentru prima dată, utilizarea teoriei analizei dimensionale pentru modelarea matematică a procesului de separare a semințelor la sistemul de curățire de la combinele de cereale, în vederea anticipării pierderilor de semințe ale sistemului. Pe baza studiilor teoretice şi experimentale anterioare, a fost considerat în studiu un număr de şapte parametri principali care caracterizează procesul de separare. Aplicând teorema Π (Buckingham) din teoria analizei dimensionale s-au obținut criteriile de similitudine adimensionale, pentru modelul matematic care să permită anticiparea pierderilor de semințe ale sistemului de curățire pentru care s-a propus o relație explicită între criteriile de similitudine sub forma produsului de puteri, de tipul: $p/(q \cdot D_j) = k \cdot (D_j \cdot f / v_a)^a \, (L_s / D_j)^b \, \lambda^c$. *Utilizând datele experimentale obținute pe un stand de laborator prevăzut cu un sistem de curățire tradițional cu caracteristici constructive şi funcționale cunoscute, s-a testat valabilitatea relației propuse. S-au găsit valorile coeficienților* $k = 0.137 \cdot 10^{20}$; $a = 4.901$; $b = -5.640$; $c = -5.257$, *pentru un coeficient de corelație* $R^2 \cong 0.837$.

Aceasta probează că modelul matematic propus poate fi utilizat la anticiparea cu suficientă precizie a pierderilor de semințe la sistemul de curățire al combinei comparativ cu pierderile reale obținute la experimentări, fiind util atât proiectanților cât şi utilizatorilor combinelor prevăzute cu un astfel de sistem.

For the first time in this paper the theory of dimensional analysis for a mathematical model of the process of seeds separation is analyzed at the cleaning system level of the cereal harvester combines, in order to predict the seeds losses of the system. Relaying on theoretical studies and previous experiments, seven most important parameters that are characteristic for the separation process, were taken into consideration. Applying Buckingham Π theorem from the dimensional analysis theoretical basis, as a result the following criteria of dimensional similitude for the mathematical model used for the losses reduction in the cleaning system, a clear relation was determined between the similar criteria as an equation of the following type: $p/(q \cdot D_j) = k \cdot (D_j \cdot f / v_a)^a \, (L_s / D_j)^b \, \lambda^c$, *where: q (kg/m/s) is the specific feed rate flow;* v_a *(m/s) – the air velocity;* λ – *the masses ratio between material other than grains (m.o.g.) and seeds;* D_j *(m) – the orifices opening of Petersen cleaning system;* f *(s^{-1})*

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– the oscillation frequency of the sieves; L_s (m) – the length of the sieves; p (kg/s) the seeds losses and k, a, b, c –coefficients determined according the experiments data. The suggested relation was tested having the data of the experimental research on a laboratory stand equipped with a traditional cleaning system with already known constructive and functional characteristics. The following coefficients values were obtained $k = 0,137 \cdot 10^{20}$; a = 4,901; b = –5,640; c= –5, 257, for a correlation coefficient $R^2 \cong 0,837$.

This paper proves that the suggested mathematical model can be use in order to predict with accuracy the losses of seeds in a cleaning system of the cereals harvest combine. This model may be used by the harvest combine designers as well as by any user.

Key words: cereal harvesting combines, cleaning system, seeds losses, dimensional analysis, and mathematical model

1. Introduction

The cleaning system of the harvesting combines is a functional sub-device inside which the separation of the seeds takes place. The process of seeds separation from the top on the sieve of the system is complex process influenced by multiple variable factors, most of them with random characteristics, only a few number of them under control. Therefore the analytical mathematical modeling of the separation process is quite difficult, [1–8].

One of the most important parameters of the cleaning system performances is represented by the seeds losses in the superior sieve of the cleaning system [1–8].

The study of the seeds separation process on the length of the sieve has represented the main subject for many theoretical research and practical experiments where the suggested mathematical model allows, generally, predicting the seeds losses in particularly working conditions. [1–8].

In the paper [1] a model type exponential function is suggested. This model is determined by comparing the separation process with diffusion process expressed by Fick law. In papers [2,3,8], are suggested empirical models as exponential functions describing in a proper way the separation process based on experimental data; in papers [4,5] we demonstrate that the logistic function with two parameters and Rosin – Rammler function of the granulometric curve of a granular material are describing in an accurate way the process separation on the cleaning system (proved by the high values of correlation coefficient, $R^2 \geq 0.97$), [5]).

In order to clearly explain the mathematical model and its main parameters in the system, in [6] the logistic model was developed, suggesting a logistic model with a multiple linear regression.

The theoretical mathematical model logistical equation type for the combine system for seeds separation theoretical background is given in paper, [7].

In this paper the authors deal for the first time with the use of dimensional analysis for a mathematical model of the seeds separation on top of the sieve, due to the complexity of the process [9,10].

The aims of the present paper are: a) determination of similitude dimensionless criteria of the separation process according to the dimensional analysis theory, [9,10]; b) obtaining the correlative predicted function between the given similitude criteria c) testing the availability of the suggested mathematical model according the experimental data; d) application of the given mathematical model for the seeds losses prediction in the cleaning system, in practical circumstances.

2. Theoretical basis

According to the theory of dimensional analysis the process of seeds separation on the top sieve of the cleaning system can be described taking into consideration the most important of its parameters [9,10]. In the analysis performed for this paper, according to previous studies [1–8], a number of seven most important parameters such as: q (kg/m/s) is the specific feed rate flow of the cleaning system; v_a (m/s) – the air velocity when getting out of the cleaning system fan; D_j (m); the orifices opening of Petersen sieves of the cleaning system, measured between the planes of two plates with adjustable orifices; f (s^{-1}) – the oscillation frequency of the sieve frame; p (kg/s) – the seeds losses at the superior sieve edge of the cleaning system; L_s (m) – the length of the sieve on which separation takes place; λ (dimensionless) – ratio between the m.o.g. (material other than grains*)* quantity and seeds at sieve feed rate.

Seeds losses p were expressed in the same measurement system as the supply flow in order to simplify the application of analysis method.

The functional link between the system parameters and performance items p can be dimensionally described according the homogenous implicated function:

$$f\,(q, v_a, D_j, f, \lambda, L_s, p) = 0 \tag{1}$$

This equation has seven variables. The reduction of the variable number describing the separation process is due to the application of Buckingham Π theorem for the determination of the complex dimensionless arguments (called similitude criteria), which helps the process description. If the separation process is analyzed according the losses level, the connected function (1) is homogenous from the dimensional point of view, has an availability for all the fundamental measurement units in use. The dimensional matrix of the physical parameters of the connected function (1) written with the fundamental dimensions interfering in the dimensional equation of the system parameters and those of the process has the following shape:

$$\begin{array}{c|ccccccc|} & x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 \\ & q & v_a & D_j & f & \lambda & L_s & p \\ M & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ L & -1 & 1 & 1 & 0 & 0 & 1 & 0 \\ T & -1 & -1 & 0 & -1 & 0 & 0 & -1 \end{array} \tag{2}$$

The first three columns were chosen as basic dimensions of the matrix. Any of the considered physical values can be selected if the conditions in which the theorem is applied are respected [9,10], and at the same time they should allow few modifications when tested on the physical model.

The process of seeds separation is a mechanical process, implying the selection of a three basic parameters [9,10], meaning: q, v_a and D_j. That is why the other parameters (f, λ, L_s, p) are secondary parameters, meaning that the number of complex dimensionless arguments according to which the process is evaluated should be four.

When other basic parameters of the matrix are selected, the complex dimensionless arguments of the result are combinations of the complex dimensionless arguments previously determined.

The dimensional matrix (2) rank is k = 3 and the main determinant value is equal to the three order minor, on the left of the matrix, different of zero ($\Delta = +1$).

The expression (1), written with dimensionless arguments can be transformed in a function named criterial function containing four variable, complex dimensionless arguments Π_i.

In its new formula the function (1) becomes:

$$F(\Pi_1, \Pi_2, \Pi_3, \Pi_4) = 0 \tag{3}$$

The unique determination formula of the complex dimensionless arguments suggested in [9], is:

$$[\Pi_i] = [q]^{x_1} [v_a]^{x_2} [D_j]^{x_3} [f]^{x_4} [\lambda]^{x_5} [L_s]^{x_6} [p]^{x_7} = M^o L^o T^o \tag{4}$$

Replacing in relation (4) the values from the matrix (2) we have the following system of equation:

$$\begin{cases} x_1 + x_7 = 0 \\ -x_1 + x_2 + x_3 + x_6 = 0 \\ -x_1 - x_2 - x_4 - x_7 = 0 \end{cases} \tag{5}$$

Separating the main variableness x_1, x_2, x_3 and solving the system (5), we have:

$$\begin{cases} x_1 = -x_7 \\ x_2 = -x_4 \\ x_3 = x_4 - x_6 - x_7 \end{cases} \tag{6}$$

Selecting secondary parameters values x_4, x_5, x_6, x_7, so that these values should become a sub matrix unit and replacing those values in equation (6) the result x_1, x_2 şi x_3 and the matrix for complex dimensionless arguments is built up, having the following aspect [9,10]:

$$\begin{array}{c|ccccccc|} & x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 \\ & q & v_a & D_j & f & \lambda & L_s & p \\ \Pi_1 & 0 & -1 & 1 & 1 & 0 & 0 & 0 \\ \Pi_2 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ \Pi_3 & 0 & 0 & -1 & 0 & 0 & 1 & 0 \\ \Pi_4 & -1 & 0 & -1 & 0 & 0 & 0 & 1 \end{array} \tag{7}$$

The complex dimensionless arguments are built up with the exponents from the (7) having the aspect due to the following relations:

$$\Pi_1 = \frac{f \cdot D_j}{v_a} = const. \qquad \Pi_2 = \lambda = const. \tag{8'}$$

$$\Pi_3 = \frac{L_s}{D_j} = const. \qquad \Pi_4 = \frac{p}{q \cdot D_j} = const. \tag{8}$$

Those complex dimensionless arguments show the physics law between the basic parameters and the secondary ones.

The criterial equation of the separation process according to the seeds losses level is:

$$F\left(\frac{f \cdot D_j}{v_a},\ \lambda, \frac{L_s}{D_j}, \frac{p}{q \cdot D_j}\right) = 0 \tag{9}$$

Condition Π_i=const. shows that during the process the values interfering in a certain dimensionless criterion, no matter the other parameters values, have always the same value. If these value α_i, the result is:

$$\frac{f \cdot D_j}{v_a} = \alpha_1 \qquad \frac{L_s}{D_j} = \alpha_2 \tag{10}$$

$$\lambda = \alpha_3 \qquad \frac{p}{q \cdot D_j} = \alpha_4$$

were, intuitional the resulted expressions are true and are supposed to determine experimentally the constants α_i. One can see that the balance m.o.g./seeds = λ, represents a constant of the separation process; in experimental conditions on the model it should have the same values as on the machine.

Analyzing the expression of the other three complex dimensionless arguments one may surmise that the seeds losses are proportional with the supply flow of the cleaning system and the orifices opening of the sieve, in separation process.

The major facility of theorem Π consists of the fact that no matter which the expression (10) only one experimental determination with the measurement of the values interfering in complex dimensionless arguments is necessary to determine constant α_i.

Underlining the influence of the main parameters regarding the seeds losses in separation process is done by combining in different ways the complex dimensionless arguments used for the criterial equation (9) or through the separate dependence of argument Π_4 (in which p interferes) in connection with the other dimensionless arguments.

An explicit expression of criterial equation (9) should be predicted as a power multiplication: $\alpha_4 = k \cdot \alpha_1^a \cdot \alpha_2^b \cdot \alpha_3^c$, or:

$$\frac{p}{q \cdot D_j} = k \cdot \left(\frac{D_j \cdot f}{v_a} \right)^a \left(\frac{L_s}{D_j} \right)^b \lambda^c \qquad (11)$$

where: k, a, b, c are constant coefficients, that should be determined according to experimental data.

Taking into consideration the all ready mentioned aspects some experimental determined values for constants α_i, are going between the four complex dimensionless arguments previously determined, in different working conditions.

3. Materials and methods

The experimental determinations were made in the laboratories of the Biotechnical Systems Chair of the Faculty of Biotechnical Systems Engineering from "Politehnica" University of Bucharest on a stand that has the constructive and functional characteristics of the traditional cleaning system from harvesting combines, where controlled working conditions ere established.

A sieve with opening orifices (Petersen type) a total length of L=1200 mm and 220 mm width was used. The sieve was added at an angle of the 7^o horizontal.

The material used for experiments consisted of wheat stroke of Romanian brand Fundulea 4 from a C-12 combine (made in Romania), during the harvest time, with the following main characteristics: bulk density of the seeds 775÷800 kg/m^3; 1000 seeds mass 38,6...43,5 g; seeds moisture content 11,3÷12,5%; bulk density of m.o.g. 62,3-65,9 kg/m^3; the ratio material other than grains /seeds, λ = 0,2…0,3.

Seeds that passed through the sieves orifices were collected in a drawer under the sieve so that by moving during the experiment only the adequate material of the working process should be collected when the sieve stays still during six seconds.

Other details concerning the constructive characteristics of the stand and working methodology are presented in woks [3,5,6,8].

4. Results and discussions

For more experimental determination made on the laboratory stand the seeds losses for four sieve length L_S, four values of the oscillation frequency f, two values of the speed of the air flow under the sieve v_a and three values of the specific supply material flow, q. The primary data established during experiments are presented in table 1.

Table 1.

Seeds losses (g), on different sieve length L_s (m)

No. sample	Sieve length Ls, (m)			
	0.75	0.90	1.05	1.20
1	f = 280 osc/min; q = 0.100 kg/dm.s; v_a = 8 m/s; D_j = 11 mm; λ = 0.250			
	177.75	63.70	19.40	14.70
2	f = 280 osc/min; q =0.155 kg/dm.s; v_a = 8 m/s; D_j = 11 mm; λ = 0.267			
	324.45	120.65	29.35	13.15
3	f = 280 osc/min; q = 0.198 kg/dm.s; v_a = 10 m/s; D_j = 11 mm; λ = 0.267			
	470.60	171.30	18.60	4.20
4	f = 190 osc/min; q = 0.098 kg/dm.s; v_a = 8 m/s; D_j = 11 mm; λ = 0.247			
	9.95	5.25	2.55	1.35
5	f = 190 osc/min; q = 0.101 kg/dm.s; v_a = 8 m/s; D_j = 9 mm; λ = 0.187			
	9.25	5.55	3.10	2.00
6	f = 190 osc/min; q = 0.102 kg/dm.s; v_a = 8 m/s; D_j = 11 mm; λ = 0.292			
	8.30	3.90	1.70	1.00
7	f = 240 osc/min; q = 0.200 kg/dm.s; v_a = 10 m/s; D_j = 11 mm; λ = 0.249			
	105.70	60.90	36.10	24.00
8	f = 335 osc/s; q = 0.10 kg/dm.s; v_a = 8 m/s; D_j = 11 mm; λ = 0.248			
	536.10	314.50	102.10	26.50

The material flow supplying the sieve was compared to its the length unit in kg/m.s. In order to get an average the seeds losses were compared to the experimental time, for a length unit of the sieve length in kg/s.

In table 2 are presented the losses values of the seeds in kg/s, for four sieve length in 8 experimental tests made in different working conditions taking into consideration the primary data from table 1 and the characteristics of the measurements on the stand previously mentioned.

For the values of the all ready mentioned parameters the four non dimensional complex arguments values were calculated. They are mentioned in table 3.

Taking into consideration the dependence of the dimensionless complex α_4, compared to the three complex dimensionless arguments α_2, α_3, trough the demonstrated suggested function (11), after linearising it by logarithm member by member this may be written like that

$$\ln\alpha_4 = \ln k + a\ln\alpha_1 + b\ln\alpha_2 + c\ln\alpha_3 \quad (12)$$

Table 2.

Mass of lost seeds p (kg/s), for different sieve lengths

No. sample	Sieve length Ls, (m)			
	0.75	0.90	1.05	1.20
1	f = 4.67 osc/s; q = 1.00 kg/m.s; v_a = 8 m/s; D_j = 0,011 m; λ = 0.250			
	0.135	0.073	0.015	0.011
2	f = 4.67 osc/s; q = 1.55 kg/m.s; v_a = 8 m/s; D_j = 0,011 m; λ = 0.267			
	0.246	0.091	0.022	0.010
3	f = 4.67 osc/s; q = 1.98 kg/m.s; v_a = 10 m/s; D_j = 0,011 m; λ = 0.267			
	0.356	0.130	0.014	0.003
4	f = 3.17 osc/s; q = 0.98 kg/m.s; v_a = 8 m/s; D_j = 0,011 m; λ = 0.247			
	0.008	0.004	0.002	0.001
5	f = 3.17 osc/s; q = 1.01 kg/m.s; v_a = 8 m/s; D_j = 0,009 m; λ = 0.187			
	0.007	0.004	0.002	0.001
6	f = 3.17 osc/s; q = 1.02 kg/m.s; v_a = 8 m/s; D_j = 0,011 m; λ = 0.292			
	0.006	0.003	0.001	0.001
7	f = 4.00 osc/s; q = 2.00 kg/m.s; v_a = 10 m/s; D_j = 0,011 m; λ = 0.249			
	0.080	0.046	0.027	0.018
8	f = 5.58 osc/s; q = 1.00 kg/m.s; v_a = 8 m/s; D_j = 0,011 m; λ = 0.248			
	0.406	0.238	0.077	0.020

Replacing in relation (12) the values of the complex dimensionless arguments α_i^j, from table 3, the result is a system of 32 equation with four unknown terms (k, a, b, c) solved with multiple linear regressive analysis in program MicroCall Origin vers.6.0.

Scrolling on the computer we are found the values of constant k and of exponents a, b, c: $k = 0.137\cdot10^{20}$; a = 4.901; b = –5.640; c= –5.257.

Using these values, relation (11) which shows the dependence of seeds losses in process versus others process parameters take in study, it will become:

$$\frac{p}{q\cdot D_j} = 0.137\cdot10^{20}\cdot\left(\frac{D_j\cdot f}{v_a}\right)^{4,901}\cdot\left(\frac{L_s}{D_j}\right)^{-5.64}\cdot\lambda^{-5.257} \quad (13)$$

Table 3.

The values of dimensionless complex α_i, for eight samples

Sp. no.	$\alpha_4 = \frac{p}{q \cdot D_j}$	$\alpha_1 = \frac{f \cdot D_j}{v_a}$	$\alpha_2 = \frac{L_s}{D_j}$	$\alpha_3 = \lambda$	Sp. no.	$\alpha_4 = \frac{p}{q \cdot D_j}$	$\alpha_1 = \frac{f \cdot D_j}{v_a}$	$\alpha_2 = \frac{L_s}{D_j}$	$\alpha_3 = \lambda$
1	12.2438	0.0064	68.1818	0.25	5	0.7501	0.0036	83.3333	0.187
	6.6198	0.0064	81.8182	0.25		0.4500	0.0036	100.0000	0.187
	1.3347	0.0064	95.4545	0.25		0.2500	0.0036	116.6667	0.187
	1.0124	0.0064	109.0909	0.25		0.1500	0.0036	133.3333	0.187
2	14.4228	0.0064	68.1818	0.267	6	0.5672	0.0044	68.1818	0.292
	5.3586	0.0064	81.8182	0.267		0.2836	0.0044	81.8182	0.292
	1.3063	0.0064	95.4545	0.267		0.1215	0.0044	95.4545	0.292
	0.5865	0.0064	109.0909	0.267		0.0810	0.0044	109.0909	0.292
3	16.3620	0.0051	68.1818	0.267	7	3.6364	0.0044	68.1818	0.249
	5.9583	0.0051	81.8182	0.267		2.1074	0.0044	81.8182	0.249
	0.6470	0.0051	95.4545	0.267		1.2397	0.0044	95.4545	0.249
	0.1461	0.0051	109.0909	0.267		0.8264	0.0044	109.0909	0.249
4	0.7168	0.0044	68.1818	0.247	8	36.9421	0.0077	68.1818	0.248
	0.3795	0.0044	81.8182	0.247		21.6529	0.0077	81.8182	0.248
	0.1687	0.0044	95.4545	0.247		7.0248	0.0077	95.4545	0.248
	0.0843	0.0044	109.0909	0.247		1.8182	0.0077	109.0909	0.248

In this situation the correlation coefficient is R^2 = 0.837, proving in an adequate way the availability of the equation (13) for the seeds losses prediction in the traditional cleaning system of the harvesting combines.

Using the values of table 2, in figure 1a it was represented the variation of seeds losses versus sieve length, for those 8 experimental samples.

Finding a fast decrease seeds losses for sieves length breakdown 1 m, the value of those losses significant stand on of concrete work conditions.

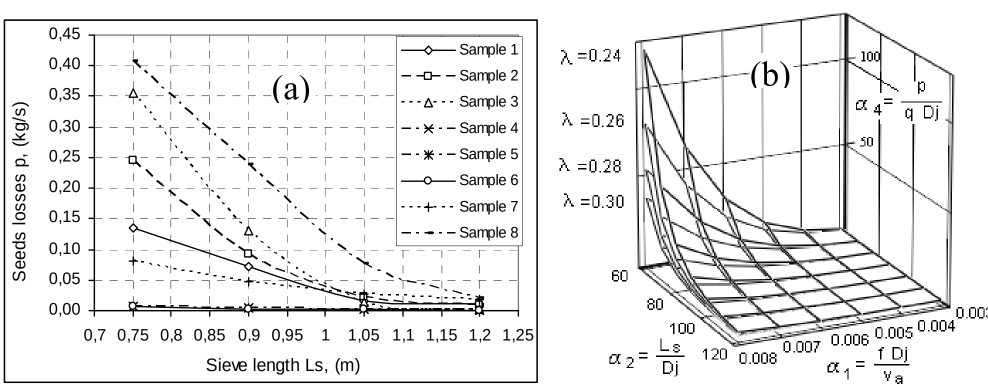

Fig.1. Seeds losses variation vs. sieve length (a) and variation of dimensionless criteria for losses α_4 vs. dimensionless criteria α_1 and α_2 for four λ values cf. eq. 13, (b)

In fig.1b, it is plotting in 3D the variation curves of dimensionless criteria α_4 (for seed losses), versus dimensionless criteria α_1 (for oscillation frequency) and α_2 (for sieve length), for four values of λ coefficient. Finding a decrease seeds losses with decrease of oscillation frequency, with increase sieve length, and with the increase of λ coefficient.

With a proper processing the equation (13) can be dispose like this:

$$p = 0.137 \cdot 10^{20} \cdot q \cdot \left(\frac{f}{v_a} \right)^{4.901} \cdot L_s^{-5.64} \cdot D_j^{11.541} \cdot \lambda^{-5.257} \tag{14}$$

Equation (14) allows the prediction with enough accuracy of the seeds losses in the cleaning system, through direct calculus, if choose the parameters values q, f, v_a, L_s, D_j, λ in the limits of the values used during the experiments.

Equation (14) was used to calculate the losses for some data in table 2 and was compared with the data of the measurements, most of differences being in the limits –12.5% and +15.8%, proving the utility and applicability of the equation (14).

5. Conclusions

In this paper the theory of dimensional analysis for mathematical modeling of seeds separation in the cleaning system of the harvesting combines in order to predict the seeds losses is used for the first time

After applying theorem Π from the dimensional analysis theory for the seeds separation processes in stroke in the cleaning system of the harvesting combines taking into consideration seven important parameters of the process, equation (11) was suggested, expressing mathematically the physical link between the seeds losses and the other parameters of the process

Testing the equation (11) with the data from the experiments, equation (13) was found, for a correlation coefficient $R^2 = 0.837$, demonstrating the availability of the suggested mathematical model

Through adequate processing of equation (13), came out the practical calculus equation (14) of the seeds losses

Those equations are important and allows the rapid estimation of the seeds losses at the end of the sieve (for cleaning systems similar with that used during the experiments, in similar working conditions) knowing the other parameters of the process and is useful for designers and users of the harvesting combines as well.

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