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# MECHANICAL ENGINEERING OF GRAIN MILLING

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Summary. This paper contains practical fundamentals of both design and milling process innovations, that make use of analogy between a grain and a machine member and that treat a grain as part of grinder design. The author has applied eco-balance method of food machines analysis. Results of research potentials studies, actively controlled towards: mathematical description of general or selected machine operation, influencing machine environment of food in both active and passive manner have also been described; whereas quality as reliability estimator means the distance between the actual system response and the response of design model.

Key words: food mechanics, machine design, environment.

## INTRODUCTION

Faculty of Mechanics at the ATR in Bydgoszcz conducts intensive research on food processing aiming at describing the field of knowledge on mechanical engineering of grain milling [4,5]. Food mechanics does not render the essence of the mechanical domain of food technology and nutrition engineering as branches of study. To show the depth of issues concerning a grinder (design) it is necessary to find the adequate field of knowledge. As it can be assumed from the earlier results, the proper field of systematics, along with the field of knowledge and innovation, comprises fundamentals of the machine building and operation, as well as food environment appliances and installations. Obviously limited to machine design theory.

## MECHANICAL FUNDAMENTALS OF MILLING

Calculations of the type and the course of cracking of milled materials has become a part of strength analyses and methodology. That naturally means calculations of approximated type of decohesion. Crushing of biological materials, including corn seed, can proceed from softly plastic to violently brittle, or from slow to fast fatigue cracking. Of course, there is a variety of crushing types between the mentioned ones. Each full decohesion is destructive from the point of view of mechanics and it is desired from the point of view of processing. However the thing is to predict probable load and milling section on the basis of laws and theorems of grinding. The type of decohesion depends also on the coincidence of several environmental factors. The most important of which are: state of stress and internal pressure, temperature, rapidity of load and external features of grinded element (mechanical, aerodynamical, electrostatic and thermal). There is also a group of non-material and non-technical features, among which the most important are: the kind of storage, intermediate transport and insolation of seed. Hence both plastic and brittle state along with all intermediate states are temporary conditions of material on the given terms of grinding.

In case the grinding load is below the immediate strength, plastic or ductile cracking is always preceded by plastic macrodistortions and it is the result of the slip (truncation) on the slip plane. Crush surfaces are characterised by the system of pits and protrusions, which form slice or flaky sections. Brittle cracking proceeds completely differently. It develops even at the speed of sound, depending on the type of raw material, conventionally in the elastic range, hence without plastic distortions, perpendicularly to the largest elongation of the biological material.

Grains of partially crystalline structure crack along certain crystal planes and along cleavage planes. The second type of brittle cracking is the intercrystalline cracking. But the most often kind is mixed cracking, i.e. partially plastic and partially brittle.

Brittle cracking is the most favourable one in terms of grinding among the above categories of cracking. They were tested very precisely using electronooptical methods. There have been long lasting searches for the best concept of milling units, which would take advantage of brittle cracking. They were accompanied by the analysis of formation and development of cracks along with stress fields and distortions analyses in the cracking area. Those studies were based on mechanical features of materials. Researchers obtained desirable solutions basing on conditions of the equilibrium of elements containing gaps and coherence failures, that were not caused by external loads.

The basis of the most considerations on brittle cracking, along with the mechanics of cracking, is Griffiths classic theory of gaps (1920 r.). A.A. Griffith tried to explain the difference (several orders of magnitude) between the actual strength and the one calculated theoretically. The subject of his interests was glass, which is amorphous body. He made an assumption that there are small gaps inside real bodies, which concentrate stress. He used in his works the earlier idea of C.E. Inglis (1913 r.?) concerning state of stress and distortion around a lenticular, flat gap. Griffith's theory has been modified many times. There was particular emphasis put on plastic distortions. However, the core of the theory has not been changed. According to it, a 2l long gap situated in a plate, which is under elastic, steady tension and its dimensions are infinite and its width measures one unit causes sort of relief in the area around the gap. So, the elastic distortion energy decreases by $\Delta U_s = -\pi l2\sigma^2/E$. At the same time there is an increase of surface energy $\gamma$, necessary to create a new surface. This energy totals $4l\gamma$ and total energy of cracking development consists of those two energies:

$$\Delta U = 4l\gamma - \frac{\pi l^2 \sigma^2}{E}. \tag{1}$$

After it has reached the maximum value, further development of cracking is described by potential energy of elastic distortion of the plate, so there is no need to provide an external energy. At this moment the gap (its critical length - $2l_{kr}$) is in the metastable state and is beginning to expand intrinsically at the speed comparable to the speed of sound, causing brittle cracking. Whereas its critical length is assisted by critical strength:

$$\sigma_{kr} = \sqrt{\frac{2E}{\pi l_{kr}}}. \tag{2}$$

Basing on that relation, completed by total energy of cracking development, one can derive a formula of decohesion susceptibility ratio 1/K.

We observe a complex state of stress during calculations of corn grinding, which combines bending, tension, compression and torsion. There are both normal and shearing stresses here.

Supposing, that random quantities of both inflicted and dismembering stresses are of normal distribution, it is possible to calculate basic indicators of seed grinding probability. The inflicted stress curve $p(\sigma)$ and the temporary stress curve, that dismember a seed $p(Z)$ have been shown in the Fig. 1.

The above curves may intersect at point A, depending on the resultant stress impacting on the ground element. If we introduce the following denotation of the

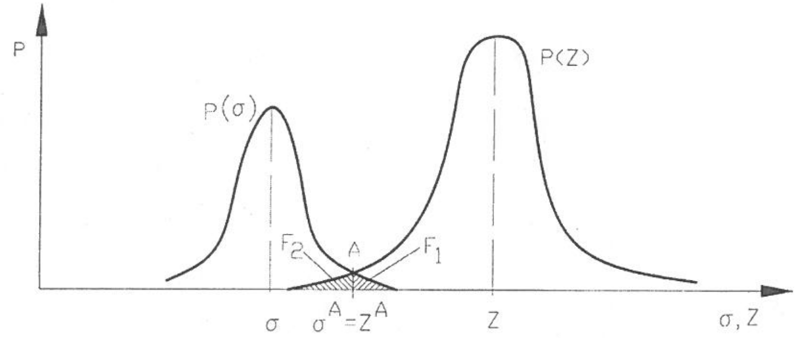

**Fig. 1.** Scheme for items grinding probability calculations [4,8]

hatched areas: $F_1 = \int\limits_{\sigma^A}^{\infty} p(\sigma)d\sigma$ and $F_2 = \int\limits_{0}^{Z^A} p(Z)dZ$ we can make an assumption, that seed grinding probability for independent random variable of stress satisfies the inequality:

$$P>F_1F_2 \tag{3}$$

for any value of inflicted stress, bigger than decohesion stress Z. The product of those areas means the probability that simultaneously $\sigma>\sigma^A$ and $Z<Z^A$ - excluding following random variable $\sigma>Z$ when $Z>Z^A$ or when $\sigma<\sigma^A$, which also respond to conditions of husk or endosperm decohesion.

Complement of the product of probabilities $(1\text{-}F_1)(1\text{-}F_2)$ goes for a case of low grindability. That's why grinding probability satisfies the inequality:

$$Q>(1\text{-}F_1)(1\text{-}F_2). \tag{4}$$

On the basis of both the above relation and the previous ones, we can finally assess the size reduction (grinding):

$$P>1\text{-}Q;\ P>F_1+F_2-F_1F_2$$

and probability of size reduction:

$$F_1F_2<P<F_1+F_2-F_1F_2 \tag{5}$$

$$F_1 = \frac{1}{2} - \Phi z\left(\frac{\sigma^A - \overline{\sigma}}{s_\sigma}\right), \quad F_2 = \frac{1}{2} - \Phi\left(\frac{Z^A - \overline{Z}}{s_z}\right). \qquad (6)$$

Supposing, that load probability distribution and grinding probability distribution are normal-type with the mean values and with standard deviations, we obtain the relation (6) where Φ is a normal Laplacian function and its values can be found in statistical tables. Symbolic meaning of such grinding analysis is worth paying attention to - because of great variety of seed characteristics and due to subjecting to the random grinding loads.

## MATERIAL AND METHOD

Design is the reason for creation, operation and "liquidation" of - "life in environment" as well as the subject of cognition of a machine [4]. Theory of grinder design is therefore the basis of innovative methodology of proceedings with biological material during grinding process.

Theory of design is made up of descriptions, models, rules and principles of food environment machines design, which can be reduced to the following criteria [4,5]:

- optimal load - the necessity to guard against harmful impact of machines on food, which might than be bad for health, environment and the design itself;
- optimal material - special requirements in relation to internal structure of working elements of a grinder as well as their machining;
- optimal stability - the necessity to ensure high standard of hygiene facility during operation of the machine, high peculiarity of some machining operation, which are very difficult to stabilize, mechanize or even, to automate; the necessity to measure, monitor and control biological features of food, previously processed in machines;
- optimal relations of related quantities - loads - distortions - stress, maintenance of high smoothness, efficiency, continuity of technological operations, traditions - progress, innovations, "novelties" for food markets.

The foundation of machine design and manufacturing process planning in production of agricultural raw materials is the knowledge about o physical quantities of those substances. It concerns different groups of features, such as, physical, chemical, biological, and generally: technological. Supposing that the ground element - during grinding process - becomes an element of the machine, so it becomes subject to design criteria. Agricultural raw materials, semi-manufactured products and final products are biologically active. According to the most general definition, it means that they contain ingredients, which are of vital importance to people and that their physical form can change significantly, also in stable thermodynamic conditions (e.g., digestibility).

## Design model of a grinder

Mentioned rules were presented in a nearly hierarchical way. They form basis for food machine design, building and operating.

Mathematical model of grinding is the mathematical description of relations between input and output with a fixed simplification degree. The following items were used while modelling [3-5]:

- the work potential equation,
- design feature matrices of a power unit and multi-disc unit,
- functions of peculiar and general research objects.

The work potential equation within a period ($t_0$,$T$):

$$P_d(T) = P_d(t_o) - \int_{t_o}^{T} p_d^E(t)dt - \int_{t_o}^{T} p_d^s(t)dt + \int_{t_o}^{T} p_d^o(t)dt \qquad (7)$$

where: $P_d(t_o)$ - initial work potential; $p_d^E(t)$ - flux density of effectively used potential; $p_d^s(t)$ - flux density of wasted potential; $p_d^o(t)$ - flux density of recreated potential (or obtained from environment).

Taking nutritional grinding aims into account we obtain:

$$P_{em}(T) = P_{em}(t_o) - \int_{o}^{T} p_{em}^E(t)dt - \int_{o}^{T} p_{em}^s(t)dt + \int_{o}^{T} p_{em}^o(t)dt \qquad (8)$$

where: $P_{em}(t_o)$ - initial energy-material potential (e-m) of grinding; $p_{em}^E(t)$ -flux density of effectively used e-m potential; $p_{em}^s(t)$ - flux density of wasted e-m potential; $p_{em}^o(t)$ - flux density of e-m recreated potential, (or only retrieved from environment).

Generally, the function of the research object is:

$$\{Hu\}: H_N = f\{C_k\},\ H_m = f\{C_k\}, H_e = f\{C_k\}, H_q = f\{C_k\} \qquad (9)$$

where: $N_u$ - power demand: $H_N = f(C_k)$; $W_u$ - mass efficiency: $H_m = f(C_k)$; $e_R$, $\eta$, $E_T$, $M$, $\omega$, $v$, $n$ - energy indicators: $H_e = f(C_k)$; $\lambda$, $q$ - product quality: $H_q = f(C_k)$.

It is aimed at, by the rule, to minimize or maximize selected characteristics. Detailed form of the research object is (for quality function) following (there are particular features of grinder design given in brackets: dimensions, speeds, circular pitches, number of holes and gaps):

$$H_q = f(d,\ d_r,\ \omega,\ t_o,\ t_r,\ l_t,\ l_o,\ l_{rz},\ s_i). \tag{10}$$

Q function is used to assess the model of research object, its quality as a measure of the difference between signals of the model and the actual object.

$$Q=||y^{*}-y|| \tag{11}$$

where: $y^*$- actual system response (e.g., grinding - process), $y$ - model response (e.g. quasi-shear phenomenon).

Detailed indicators were also used:

- specific energy consumption,
- performance and efficiency of the process.

### Specific energy consumption

While modelling, there were used such quantities like description of energy consumption ($p_e\ (t)$) compared to the amount of output seed in a given period of time ($p_{e\text{-}m}\ (t)$), i.e. specific energy consumption. Specific energy consumption $E_{JM}$ was defined generally as a relation of power ($N$) to mass rate of ground grain discharge ($G$) (mass flux of the final product) [4]:

$$E_{JM} = \frac{N}{G}. \tag{12}$$

Power was compared to the volume flow rate of the final product ($W$) and the result was a variety of specific energy consumption:

$$E_{JO} = \frac{N}{W}. \tag{13}$$

$E_{JM}$ is called specific energy mass consumption, whereas $E_{JO}$ means specific energy volume consumption. This model is not very useful in grinding. While specific energy consumption decreases, watt-hour efficiency of the process increases. Usefulness was measured by the notion of energy consumptiveness for required processing dimension (e.g. 80% of fractions with an average dimension 0.3-1.48 mm) (dedicated consumptiveness) $E_{Rq}$:

$$E_{Rq} = \frac{N}{W_{fq}} \tag{14}$$

where: $N$ - power used for grinding, $W$; $W_{fq}$ - the output, measured by the amount of ground grain with desirable, (in further nutrition) dimensions of fractions ($f_q = 0.3\text{-}1.48$ mm), kg $s^{-1}$.

**Performance and efficiency**

The performance-efficiency model was adopted as follows:

$$\Delta e_R = \frac{K}{N_E} \tag{15}$$

where: $\Delta_{eR}$ - increase of power efficiency of grinding, [-], $K$ - power benefits of grinding, [kJ $kg^{-1}$], $N_E$ - power input for grinding, [kJ $kg^{-1}$], in which the numerator and the denominator are described as:

$$\Delta e_R = \frac{(\Delta)E_{pp}}{(\Delta)E_{R\lambda(F)}} \tag{16}$$

where: $E_{pp}$ - workability energy, [kJ $kg^{-1}$], $E_R\lambda$ - grinding energy (phenomenon), e.g. to obtain the product with 0.3- 1.48 mm fraction in 80% of mass, [kJ $kg^{-1}$].

Efficiency model is described by the relation between energy in machine or phenomenon conditions:

$$\eta_{q-ś} = \frac{E_{q-ś(f)}}{E_{q-ś(m)}} \tag{17}$$

where: $\eta_{q-ś}$ - quasi-shear efficiency, [-]; $E_{q-ś\ (f)}$ - quasi-shear energy in phenomenon conditions (testing machine, badania static research), [kJ $kg^{-1}$]; $E_{q-ś\ (m)}$ - quasi-shear in real conditions (machine - specific grinding unit), [kJ $kg^{-1}$].

To assess power efficiency of quasi-shearing of seed, for nutritional purposes, we have to use the following indicator:

$$e_{RP} = \frac{(\eta_{q\text{-}ś} - \eta_o) E_{brutto} \eta_s \eta_p}{(k_j v_r + \tau_{q-ś} F_{q-ś} + \varepsilon F_R' v_r^2) M_k v_r t} \tag{18}$$

where: $\eta_{q\text{-}\acute{s}}$ - digestibility in vitro of the grinding product [-]; $\eta_o$ - digestibility in vitro of entire seed [-]; $E_{brutto}$ - energy included in the processed grain, Triticale 16.5 MJ/kg [kJ kg$^{-1}$]; $\eta_S$ $\eta_P$ - efficiency of the power transmission system of the grinder (motor and transmission) [-]; $k_j$ - idle run resistance coefficient [kg s$^{-1}$]; $v_r$ - speed of quasi-shear [m s$^{-1}$]; $\tau_{q\text{-}\acute{s}}$ - quasi-shear stress of a seed [N m$^{-2}$]; $F_{q\text{-}\acute{s}}$ - temporary section of quasi-shear of a seed or its pieces [m$^2$]; $F_R$'- secondary reaction section of quasi-shear [m$^2$]; ε -factor of proportionality [Ns$^2$ m$^{-4}$]; $M_k$ - mass-trial multiplication indicator [-].

## Technological - structural Estimators

Estimation makes use of the analysis of the function extreme (of operating characteristic) of grinding process:
$e_R$- power efficiency function [-]; $W$ - mass output of the process [kg h$^{-1}$]; $N_e$ - power demand [kW]; $E_T$ - specific energy consumption [J g$^{-1}$]; λ - degree of fineness (product dimensions) [mm]; $M$ - torques [Nm]; ω, $n$, $v$ - angular, rotational and linear velocities, rad s$^{-1}$, s$^{-1}$, m s$^{-1}$; η - efficiency [-].

Nutritional usefulness conditions are met by process parameters and design features, which maximize: efficiency function, output, degree of fineness for (relation No. 19):

$$\{C_k^* \in \phi\} : \left\{ \bigwedge_{c_k \in \phi} H_u(c_k) < H_u(c_k^*) \right\} \text{for:} H_u, : e_R, W_u . \tag{19}$$

While minimizing of power demand, specific energy consumption, dissipation of energy, torque, angular, linear and rotational velocity - (as a measure of usefulness) can be obtained by proper design features (relation No. 20):

$$\{C_k^* \in \phi\} : \left\{ \bigwedge_{c_k \in \phi} H_u(c_k) > H_u(c_k^*) \right\} \text{for:} H_u, : N_w v \ldots, n \tag{20}$$

where: $C_k^*$ - solution to the problem; Φ - permissible area of grinding vector or design features $C_k^*$ ; $H_u$ - operating characteristics.

## RESULTS AND DISCUSSION

Mill industry needs machines, which cause so called "high milling", i.e. maximum output of seed ingredients and removal of the cover layer of seed from flour.

Whereas modern trends of grinding development involve precise grinding of bran as well as entire seed [5].

The cutting edge of the grinding (cutting) tool sinks in and cuts, and at the same time acts as a wedge, which exerts pressure with its surfaces on a seed. Quasi-shear in the disc grinder shows that exactly this pressure has an influence on seed grinding process. It is assumed that ground grain is dismembered from the rest of total along certain line (so called: parting line). We deal with shear or quasi-shear depending on the force appliance - resultant of quasi-shear in relation to the parting line.

The normal component causes compression or tension stresses, whereas the tangent component - shear. Due to the fact that both tension and compression strength of a seed are twice (or more) as big as shear strength - it is also sheared along the surface under the influence of reduced stresses.

Previous research aimed at deriving the relation between normal and tangent stress vs. relations between angles as well as the relation describing circumferential force on the grinding disc [4].

Results of scientific research of multi-disc grinding process of seed with using optimal grinding unit are shown in Figs 2 and 3. The graphs determine the variety range of seed grinding efficiency and specific grinding energy consumption with reference to the gap between discs. Main research determined the influence of the speed between discs on specific energy consumption, irregularity of work and power demand.

The multi-criteria analysis, that was done basing on models (7)-(18), makes an assumption that design features meet specific indicators (criteria) [1-8] (Table 1).

To obtain sub-optimal conditions of seed grinding unit design it is necessary to take different quality of seed into account. Set of design features (Table 1), to optimise grinder design condition (19) and (20) were derived on the basis of the fulfilment of criteria - estimators verifying user-environment models of mechanical processing.

The design solution of multi-disc grinding unit (for raw material and other farm-food materials) has been verified basing on grinder process tests - carried out on the grinders during their low-volume production. Presented solution has received the first prize at World Trade of Innovations, Scientific Research and Technology in Brussels in 1998.

To obtain the postulated very high efficiency state during the control of variable features in the "material - machine - process - grinding aim" system, first, it is very important to take advantage of process possibilities, second - of material features change possibilities and third, of design feature change of the grinder.

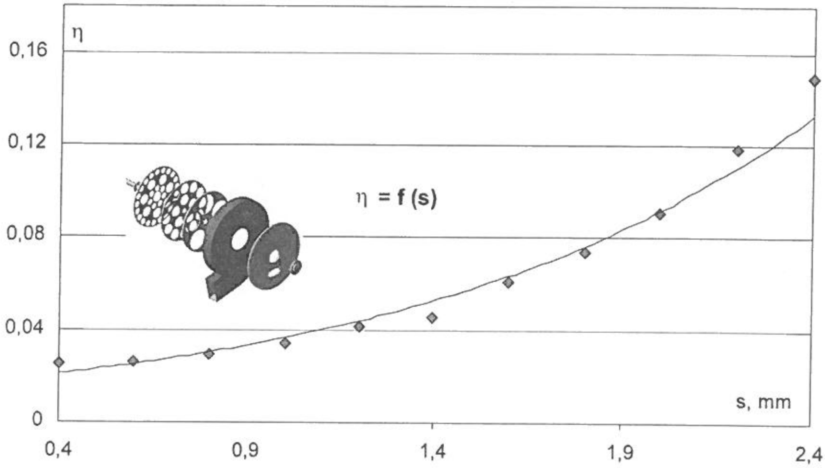

**Fig. 2.** The relation between grinding efficiency of Triticale and dimension of the gap between grinding discs $\eta = f(s)$

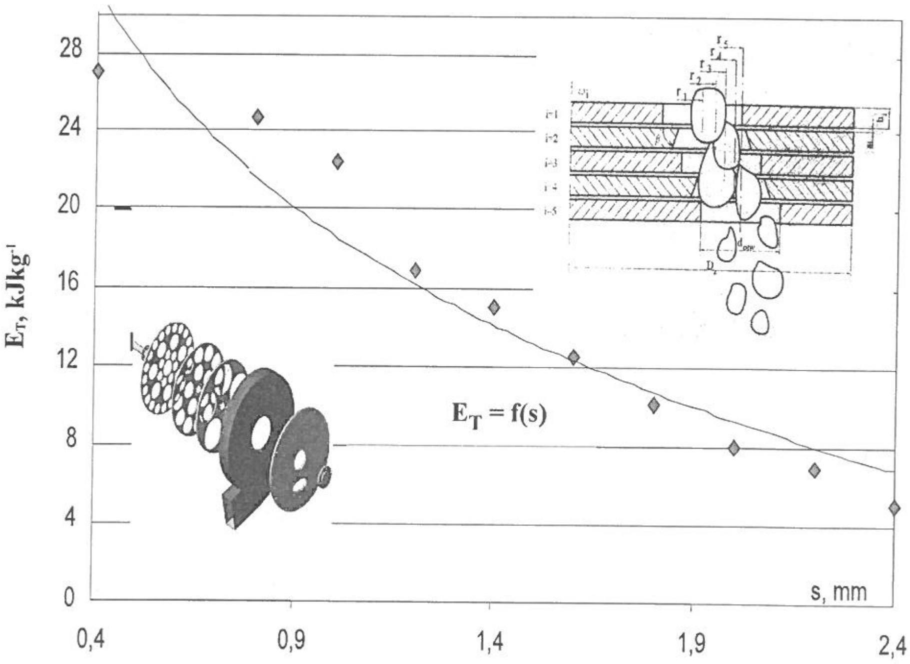

**Fig. 3**. The relation between specific energy consumption and the size of the gap between grinding discs $E_T = f(s)$, Triticale LARGO

**Table 1.** Design features of multi-disc unit, that fulfil optimisation criteria

| Multi-disc unit | $C_k \in \Phi$ – research area | $C_k^* \in \Phi$ (solution) |
|---|---|---|
| *external dia. of discs | $D_t = (430 \div 500)$ mm | $D_t^* = 500\ \mu\mu$ |
| *diameters of holes | $d = (15 \div 180)$ mm | $d^* = (15,180)$ mm |
| *hole spacing diameter | $d_r = (200 \div 400)$ mm | $d_r^* = (200 \div 400)$ mm |
| *hole edge angles | $\gamma = (60 \div 120)^o$ | $\gamma = (60 \div 75)^o$ |
| *roughness | $R_a = 10$ µm | $R_a^* = 10$ µm |
| *circular and radial pitch | $t_0/t_0\}$ acc. to hole spacing | $t_0/t_0\}$ acc. to hole spacing |
| *number of discs | $l_t = 1 \div 9$ | $I_t^* = 5\ op\ 7$ |
| *number of hole in the first disc | $l_o = 5 \div 35$ | $I_o^* = 9\ op\ 11$ |
| *number of hole lines in one disc | $l_{rz} = 1 \div 3$ | $I_{rz}^* = 2$ |
| *gap between discs | $s_i = (0.01 \div 3.1)$ mm | $s_i^* = (0.01 \div 0,1)$ mm |

Effectiveness of grinding can be assessed at least from two points of view: indicators and potentials. Efficiency indicators are related to efficacy, i.e. smooth realisation of needed aim function; economy, as a model broadened with socio-environmental aspects; informativeness - as approaching the absolute ideal (model); and durability - as relations between specific and extreme durability.

Among design solutions of seed grinders, the most preferred are multi-edge grinders, and among those - multi-hole grinders, which general shape and design features of grinding area can be determined empirically.

So, food engineering progress requires monitoring, measurement and scientific description of growing number of physical and mechanical qualities of food raw materials, in order to design machines and plan technological processes properly.

## CONCLUSIONS

Designers of food processing machines depend on the progress of knowledge in the food engineering and even, in nutrition of man [1,2].

Some food industry machines design solutions concern "biotechnology", referring to solutions that can be found in living organisms [1-3].

Mechanical engineering of food, will concern application of achievements of mechanics and other sciences in growing, processing, storage, transport, serving and "liquidation" of food.

Innovations (rapid change into a higher level of technology development) have played a crucial role in various areas of food production and processing.

Another important task of food grinding engineering is to minimise environmentally harmful effects of intense production of food products, because it is impossible to abruptly stop automation, mechanisation and chemicalisation of agriculture.

This paper indicates chosen aspects of relations between mechanical engineering of seed grinders, building and operation of machines, mechanics, chemistry, agriculture, production and processing in the food environment.

Progress of design, material, food and energy processing - as a basic area of action - will probably develop the same as mutual relations between: the level of technology and the food perpendicular on the environmental diagonal.

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## INŻYNIERIA MECHANICZNA ROZDRABNIANIA ZIARNA

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Streszczenie. W pracy zaprezentowano praktyczne podstawy innowacji konstrukcji i procesu rozdrabniania, wykorzystujące analogię między ziarnem i elementem maszynowym, traktujące ziarno jako element konstrukcji rozdrabniacza. Wykorzystano metodę ekobilansowej analizy maszyn środowiska żywności. Wyniki badań potencjałów badawczych, sterowanych adaptacyjnie w kierunku: opisów matematycznych wybranego lub ogólnego potencjału działania, wpływającego na maszynowe środowisko żywności w sensie czynnym i biernym; przy czym jakość - estymator niezawodności rozumiana jest jako odległość między odpowiedzią układu rzeczywistego, a odpowiedzią modelu konstrukcji.

Słowa kluczowe: mechanika żywności, konstrukcja maszyn, środowisko.