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### H. Inter – and Transdisciplinarity in Science and Technology

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## Synergy and matter behavior, a new approach

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**Abstract.** Until now synergistic effect is considered only the case when the final effect of the simultaneous action of several loads is greater than the sum of the partial effects. But the sum refers only to linear behavior of matters.

In the general case of nonlinear matter behavior the paper shows that the synergistic effect may be positive (the total effect is greater the sum of the individual effects), negative (the total effect is less the sum of the individual effects) or zero (the total effect is equal the sum of the individual effects). The synergistic effect depends on the matter behavior.

Some general examples and practical examples allowed a generalization of the problem of synergistic effect.

**Key words:** Synergy; linear behavior; nonlinear behavior; interdisciplinarity; synergistic effects.

### 1. Introduction

The concept of *synergy* comes from the Greek word *synergos* which means „to work / act together”, to achieve a certain goal/effect.

In general, *synergy* means the association or cooperation of several factors to produce a certain effect, which cannot be achieved through the individual actions of the factors involved. Synergy is related to an *interdisciplinary field*.

At present, *synergy* often means the simultaneous action, in the same sense, of several loads, with a *final effect that is greater than the sum of the partial effects corresponding to each load*.

The evaluation of the synergistic effects was done at the macroscopic level [1; 2], as well as at the cellular or molecular level [3]. Molecular evaluation is particularly important in analyzing the influence of any actions on living organisms, like drugs

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synergism quantification, nutrients and pharmaceuticals combination [4]. Any traditional systems of medicine may have a synergistic approach [5].

These all cases corresponds to the traditional definition of synergistic effects (the effect of the whole is greater than the sum of the effects of the individual parts). The *International Journal of Synergy Research in Life Science*, for example, is dedicated to application of synergy concept at the molecular, cellular and organisms levels, in the prevention and treatment disease.

However, only sometimes is the final effect greater than the sum of individual effects. There are times when the final effect is equal to, or even less than, the sum of individual effects. This is why it is easier to say synergy than to prove [6].

The following argumentation mathematically shows that *the synergistic effect may be positive, zero or negative*. This depends on the behavior of the matter in relation to the load to which it is subjected.

## 2. The influence of matter behavior on synergistic effect

- In the case of *linear behavior*, a load  $Y$  on a physical body determines an effect  $X$ , between which the correlation is linear, of the form,

$$Y = B \cdot X, \quad (1)$$

where  $B$  is a constant of the material under load. For example, when bending a bar, placed on two supports (Fig. 1), the following are obtained [7],

– arrow  $x_1$  under force  $F_1$ ; – arrow  $x_2$  under force  $F_2$ ; – arrow  $x_{1,2}$  – under the sum force.

In the case of the linear-elastic behavior of the bar (1),

$$x_{1,2} = x_1 + x_2, \quad (2)$$

that is, the effect of the action of the total force is equal to the sum of the individual effects. *The synergistic effect is zero*.

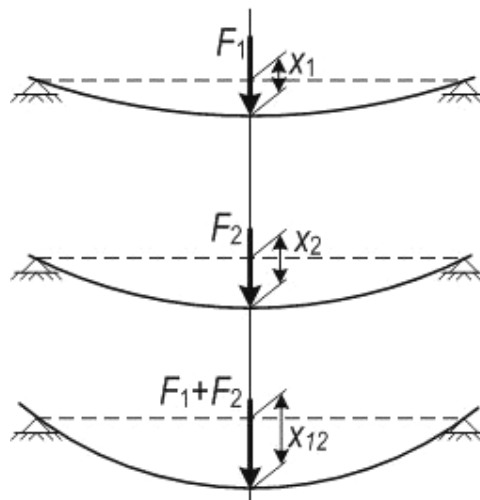


Fig. 1.

Relation (2) expresses the classical principle of superposing effects according to which „the total effect ( $X$ ) is equal to the sum of individual effects ( $X_i$ )”,

$$X = \sum_i X_i. \tag{3}$$

This relation is valid only if: - the  $X_i$  effects are measured with the same unit of measurement; - the dependence between the load and the effect is linear (1).

With a few exceptions, most of the laws of behavior currently used in various chapters of science are linear [8]. For example: Hooke's law, Newton's laws, Ohm's law, Fourier's law, Fick's law, the law of magnetic induction, etc.

In the case of nonlinear behavior, depending on power, the law is used [8; 9],

$$Y = C \cdot X^k, \tag{4}$$

where  $Y$  has the meaning of a generalized load, which may be at macroscopic or microscopic level, as well as at molecular or cellular level.  $C$  and  $k$  are material constants.

Using relation (3) in the case of nonlinear behavior leads to incorrect results. If two loads of the same nature and type,  $Y_1$  and  $Y_2$  act on a nonlinear physical body (4) and produce the main effects  $X_1$  and  $X_2$ , then  $Y_1 = C \cdot X_1^k$  and  $Y_2 = C \cdot X_2^k$ .

If the total load ( $Y = Y_1 + Y_2$ ) produces the total effect  $X$ , one may write

$$Y = C(X_1^k + X_2^k)$$

and respectively,

$$Y = C \cdot X^k.$$

From the comparison of the last relations it results,

$$X = (X_1^k + X_2^k)^{\frac{1}{k}}, \tag{5}$$

which shows that in the case of nonlinear behavior,

$$X \neq X_1 + X_2$$

or in general,

$$X \neq \sum_i X_i, \tag{6}$$

that is, the total effect is different from the sum of partial effects.

One defines:

- the *positive synergistic effect* if the total effect is greater than the sum of individual effects;
- the *negative synergistic effect*, if the total effect is less than the sum of individual effects;
- the *zero synergistic effect*, if the total effect is equal to the sum of individual effects.

If the effect of two or more actions on a body is stronger / greater than the sum of the individual effects determined by each action, it means that the total effect  $X$  fulfills the condition,

$$X > \sum_i X_i, \quad (7)$$

where  $X_i = f(Y_i)$ . Such a correlation defines positive synergy and it is obtained if the exponent from the law of behavior (4)  $k < 1$ . For example, with  $X_1 = 2$  and  $X_2 = 9$  we obtain  $\sum_i X_i = 11$ .

If the matter behaves nonlinearly and is characterized by  $k = 0.5$  then, according to relation (5) one gets  $X = (2^{0.5} + 9^{0.5})^{1/0.5} = 19.485$ , which is greater than  $X_1 + X_2 = 11$ .

If the total effect of several simultaneous loads is less than the sum of the individual effects, then

$$X < \sum_i X_i, \quad (8)$$

where  $X_i = f(Y_i)$

Relation (8) defines the negative synergy, which results if the exponent  $k > 1$ . For example, with  $k = 2$  the result is  $X = (2^2 + 9^2)^{1/2} = 9.2195$ , which is less than the sum  $X_1 + X_2 = 11$ .

In conclusion, for:

$k < 1$  one obtains a *positive synergistic effect*; the total effect is greater than the sum of partial effects;

$k = 1$ , *zero synergistic effect*, the total effect is equal to the sum of partial effects;

$k > 1$ , one obtains a *negative synergistic effect*, because the total effect is less than the sum of partial effects.

It follows that *the synergistic effect is a consequence of the value of the exponent in the law of matter behavior*.

The influence of matter behavior upon the synergistic effect may be easily understood from the graphics of matter behavior in the figure 2.

In case exponent  $k < 1$  (Fig. 2, a), under the same stress  $Y_1$ , the effect  $X'_2$  for the material whose exponent  $k < 1$  is greater by  $\Delta X'_{21}$  than  $X_1$ , corresponding to an exponent  $k = 1$ . For  $k > 1$  (Fig. 2, b) an effect  $X''_{21}$  results which is smaller by  $\Delta X''_{21}$  than  $X_1$ .

Under the same load  $Y_1$ , the effect is different depending on exponent  $k$  in the law of behavior, namely:

$$X'_2 = X_1 + \Delta X'_{21} \text{ -- if } k < 1 \text{ (Fig. 2, a);}$$

$$X_2'' = X_1 - \Delta X_{21}'' \text{ - if } k > 1 \text{ (Fig. 2, b).}$$

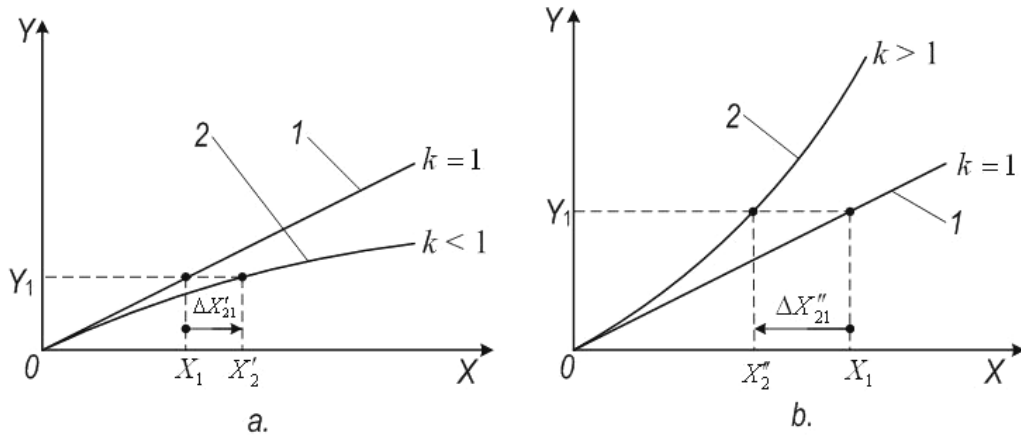


Fig. 2.

Under the action of several loads  $Y_i$ , one may write that,

$$\sum_i Y_i = C \cdot \sum_j (X_1 + \Delta X'_{21})_j^k \text{ - for, } k < 1 \text{ which corresponds to positive synergy;} \tag{9}$$

$$\sum_i Y_i = C \cdot \sum_j (X_1 - \Delta X''_{21})_j^k \text{ - for, } k > 1 \text{ which corresponds to negative synergy;} \tag{10}$$

$$\sum_i Y_i = C \cdot \sum_j X_{1,j} \text{ - for, } k = 1, \text{ lack of synergy.} \tag{11}$$

### 3. Practical examples

Some examples [10]:

- when the effects of sulfur dioxide superposes with particles in suspension, such as for instance ash dust, a *positive synergistic effect* is obtained. The combination of these pollutants may increase mortality from cardiorespiratory disorders and deficiencies of lung function;
- short-term exposure to nitrogen oxides (especially NO and NO2) leads to changes in respiratory function (emphysema, increased susceptibility to bacteriological infections of the lungs), but if they are mixed with ozone, as well as in the presence of suspended dust, nitrogen oxides have *positive synergistic effects*.

• In Rheology and in Fluid Mechanics one comes across fluids that are:

- *Newtonian*, whose behavior is defined by Newton's law,

$$\tau = \mu_0 \cdot \dot{\gamma}, \tag{12}$$

where  $\tau$  is the shear stress;  $\dot{\gamma} = d\gamma/dt$  is the shear rate ( $\gamma$  – shear strain;  $t$  - time);  $\mu_0$  - shear viscosity, constant; - *non-Newtonian*, whose behavior is given, by example, by the Ostwald-de Waele law,

$$\tau = K_\tau \cdot \dot{\gamma}^\nu, \tag{13}$$

wherein  $K_\tau$  and  $\nu$  are fluid constants.

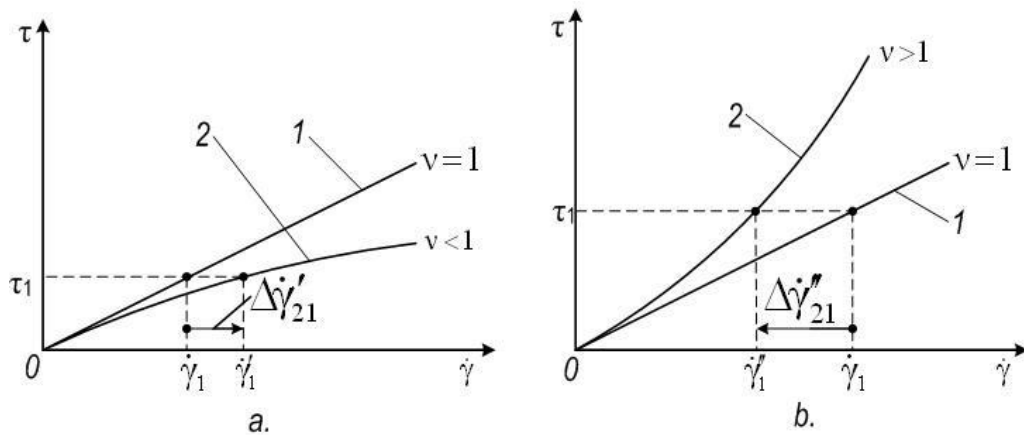


Fig. 3.

One can also find synergistic effects when fluids flow. Fluid rheograms show dependence  $\tau - \dot{\gamma}$  (Fig. 3), which resembles Figure 2. Fluid with  $\nu < 1$  are called *pseudoplastic* (Fig. 3, a), and those with  $\nu > 1$  are called *dilatant* (Fig. 3, b) [11]. One notices that:

$$\dot{\gamma}'_1 = \dot{\gamma}_1 + \Delta\dot{\gamma}'_{21} \text{ - for } \nu < 1, \text{ positive synergistic effect;}$$

$$\dot{\gamma}''_1 = \dot{\gamma}_1 - \Delta\dot{\gamma}''_{21} \text{ - for } \nu > 1, \text{ negative synergistic effect.}$$

Here  $\dot{\gamma}_1$  is the shear rate corresponding to the linear relationship (12) between  $\tau$  and  $\dot{\gamma}$ .

Consequently, taking into account a load with shear stress  $\tau$ , it may be generally written

$$\left. \begin{aligned} \sum_i \tau_i &= K_\tau \cdot \sum_j (\dot{\gamma} + \Delta\dot{\gamma}'_{21})_j^\nu \text{ - if } \nu < 1; \text{ positive synergy;} \\ \sum_i \tau_i &= K_\tau \cdot \sum_j (\dot{\gamma} - \Delta\dot{\gamma}''_{21})_j^\nu \text{ - if } \nu > 1; \text{ negative synergy.} \end{aligned} \right\} \tag{14}$$

In the case of linear behavior, (12),  $\sum_i \tau_i = \mu_0 \cdot \sum_j \dot{\gamma}_j$  - lack of synergy.

• In the case of *chemical reactions*, the synergistic effects separate exothermic reactions from endothermic reactions. For example, consider a reaction between two substances A and B, from which two other substances C and D are obtained. During the chemical reaction a certain amount of energy is released or absorbed. You can write,



The amount of energy  $\Delta E$  :

- is *released* during the chemical reaction as a result of the transition from the energy level  $E_1$  of system  $(A + B)$  to the  $E_2 < E_1$  energy level of the system. The energy  $\Delta E = E_1 - E_2$  released by the chemical reaction is the *intermolecular (chemical) binding energy*. In this case the reaction is *exoergonic or exothermic*;

- must be *added* to the system  $(C + D)$  in order to pass from the energy level  $E_2 < E_1$  to the energy level  $E_1$  of the system of substances  $(A + B)$ . In this case, the reaction is *endoergonic or endothermic*. The amount of energy  $\Delta E$  is transformed - during the reaction - into chemical energy; it is incorporated into the system of chemical substances.

The difference between the sum of the internal energies of the reactants  $E_r (\equiv E_1)$  and the sum of the internal energies of the reaction products  $E_{pr} (\equiv E_2)$  appears, most often, in the form of heat, Q. If the reaction takes place with volume variation, the difference  $\Delta E = E_r - E_{pr}$  appears in the form of heat and mechanical work, W.

Seldom does the energy difference  $\Delta E$  appear in the form of electricity or light.

The comments on the reactions complying with (15) substantiate the connection between the energies involved in the processes accompanied by chemical reactions, contained in the law established by Lavoisier and Laplace, namely:

„the amount of heat absorbed in a chemical reaction is equal to the amount of heat released in the reverse reaction.”

Between the total internal energy of the reactants,

$$E_r = \sum_i E_{r,i} , \quad (16)$$

and the total internal energy of the reaction products,

$$E_{pr} = \sum_j E_{pr,j} , \quad (17)$$

where  $i$  can be equal to  $j$  or, differently from it, the general relation can be written,

$$\left. \begin{aligned} E_r &= A \cdot E_{pr}^{k_E} \\ \sum_i E_{r,i} &= A \cdot \sum_j E_{pr,j}^{k_E} \end{aligned} \right\} \quad (18)$$

wherein  $A$  and  $k_E$  are system constants consisting of reactants and reaction products.

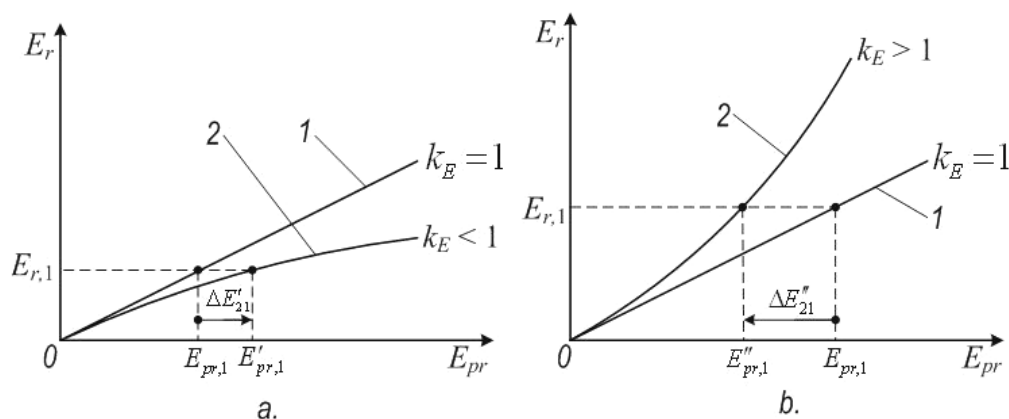


Fig. 4.

Depending on the value of  $k_E$ , in the graphical representation  $E_r - E_{pr}$  (Fig. 4) we can find two cases similar to those analyzed in figures 2 and 3.

In figure 4, a

$$E_{pr} = E'_{pr,1} = E_{pr,1} + \Delta E'_{21}, \text{ for } k_E < 1, \quad (19)$$

the reaction is exoergonic, or exothermic and corresponds to the *positive synergistic* effect.

In figure 4, b

$$E_{pr} = E''_{pr,1} = E_{pr,1} - \Delta E''_{21}, \text{ for } k_E > 1, \quad (20)$$

the reaction is endoergonic, or endothermic and corresponds to the *negative synergistic* effect.

Here  $E_{pr,1}$  is the energy corresponding to the reaction products in case the system ( $k_E = 1$ ) behaves linearly from the energy point of view.

Consequently:

- exoergonic / exothermic chemical reactions are the consequence of the *positive synergy of the reactants* ( $k_E < 1$ );
- endoergonic / endothermic chemical reactions are the consequence of the *negative synergy of the reactants* ( $k_E > 1$ );
- energy neutral chemical reactions are those where  $E_r = A \cdot E_{pr}$  or  $k_E = 1$ .

#### 4. Generalization

One writes  $Y_T$  for the total simultaneous action on a physical body and  $X_T$  for the total effect obtained. In the spirit of synergy the following general relation can be written

$$Y_T = X_T + \Delta X \cdot \delta_X, \quad (21)$$



wherein  $\delta_X = 1$ , in the case of positive synergy ( $k_E < 1$ ),  $\delta_X = -1$  in the case of negative synergy ( $k_E > 1$ ) and  $\delta_X = 0$ , in the case of neutral synergy ( $k_E = 1$ ).

It follows from previous evaluations that,

$$Y_T = \begin{cases} \sum_i Y_i & \text{- in rel. (9) and (10);} \\ \sum_i \tau_i & \text{- in rel. (14);} \\ \sum_i E_{r,i} & \text{- in rel. (18);} \end{cases}$$

$$X_T = \begin{cases} C \cdot \sum_j (X_1 + \Delta X_{21} \cdot \delta_X)_j^k & \text{- in rel. (9) and (10);} \\ K_\tau \cdot \sum_j (\dot{\gamma} + \Delta \dot{\gamma}_{21} \cdot \delta_X)_j^\nu & \text{- in rel. (14);} \\ A \cdot \sum_j (E_{pr} + \Delta E'_{21} \cdot \delta_X)_j^{k_E} & \text{- in rel. (18);} \end{cases}$$

$$\Delta X \cdot \delta_X = \begin{cases} \Delta X_{21} & \text{in rel. (9) and } (-\Delta X_{12}) & \text{in rel. (10);} \\ \Delta \dot{\gamma}'_{21} & \text{- in the first rel. (14) and } (-\Delta \dot{\gamma}''_{21}) & \text{in the second rel. (14);} \\ \Delta E'_{21} & \text{- in rel. (19) and } (-\Delta E''_{21}) & \text{in rel. (20).} \end{cases}$$

It results that under simultaneous (synergistic) loads there comes to the correlation between the factors of external action (loads) and the effects obtained, while the variations  $\Delta X_{21}$ ,  $\Delta \dot{\gamma}'_{21}$  and  $\Delta E'_{21}$ , that depend on the value of the exponent in the law of behavior as a power law ( $k$ ;  $\nu$ ;  $k_E$ ), make the difference between *positive synergistic* results ( $k < 1$ ;  $\nu < 1$ ;  $k_E < 1$ ), and *negative synergies* ( $k > 1$ ;  $\nu > 1$ ;  $k_E > 1$ ) or *neutral synergies* ( $k = 1$ ;  $\nu = 1$ ;  $k_E = 1$ ).

## 5. Conclusions

Synergy is related to the interdisciplinary field. Nowadays synergistic effect is only the case when the effect of the whole is *greater* than the sum of the effects of the individual parts.

Taking into consideration the nonlinear, power law, behavior of matter, the paper shows three kinds of synergistic effects, namely positive, negative and zero.

The general and practical examples of synergy analyzed allowed a useful generalization of the problem of synergistic effect.

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