2. The evolutionary model of industrial dynamics

Due to space limitations, the presentation of the model here will be confined to a general description without going into the mathematical details. The model describes the behaviour of a number of competing firms producing functionally equivalent products. The decisions of a firm relating to investment, price, profit, etc. are based on the firm's evaluation of behaviour of other, competing firms, and the expected response of the market. The firm's knowledge of the market and knowledge of the future behaviour of competitors is limited and uncertain. Firms' decisions can thus only be suboptimal. The decisions are taken simultaneously and independently by all firms at the beginning of each period (e.g. once a year or a quarter). After the decisions are made the firms undertake production and put the products on the market. The products are evaluated by the market, and the quantities of different firms' products sold in the market depend on the relative prices, the relative value of products' characteristics and the level of saturation of the market. In the long run, a preference for better products, i.e. those with a lower price and better characteristics, prevails.

Each firm tries to improve its position in the industry and in the market by introducing innovations in order to minimize the unit costs of production, maximize the productivity of capital, and maximize the competitiveness of its products on the market. The general structure of the model is presented in Figure 3.

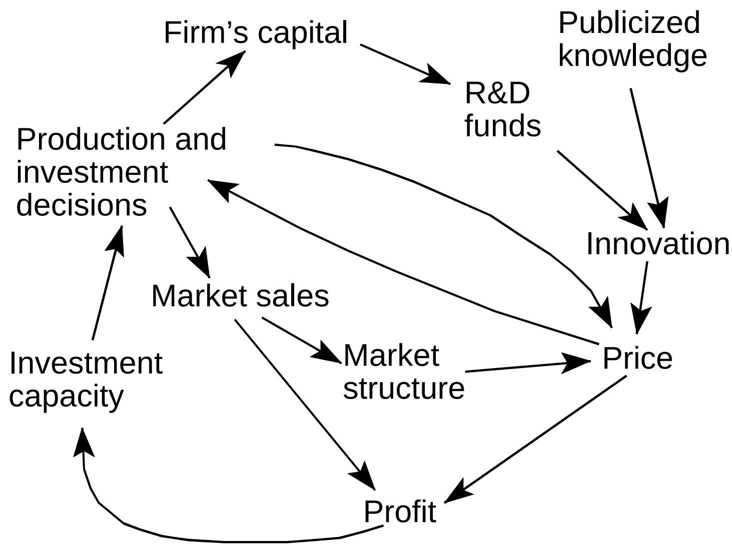

Figure 3.. General structure of the evolutionary industrial model

The product's price depends on the current technology of the firm, on market structure and on the assumed level of production to be sold on the market. The two arrows between Price and Production indicate that the price is established in an interactive way to fulfil the firms objectives (i.e., to keep relatively high profits in the near future and to assure further development in the long run). Modernization of products through innovation and/or initiating new products by applying radical innovation depends on the investment capacity of the firm. Thus, in managing innovation, each firm takes into account all economic constraints, as they emerge during the firm's development. It thus frequently occurs that to economic constraints prevent a prosperous invention from being put into practice.

One of the distinguished features of the model is the coupling of technological development and economic processes. Current investment capacity is taken into account by each firm in the decision making process. Success of each firm in the search for innovation depends not only on R&D funds spent by each firm to search for innovation, but also on the extent to which firms make private knowledge public. Making the private knowledge of a firm public can in some cases speed up industrial development, but also diminishes a firm's incentives to spend more funds on R&D projects. We may therefore expect only a certain part of private knowledge to be made public.

Firms' investment capacity depends on firms' savings and available credits, and also, indirectly, on the firm's debt. Production and investment decisions are based on the firm's expectations on future behavior of its competitors, market structure, expected profit and the past trend of the firm's market share. Current technical and economic characteristics of products offered for sale and the technology used to manufacture the products are taken into account in the price setting decisions, investment and production. Due to inevitable discrepancies between a firm's expectation and real behaviour of the market, the firm's production offered for sale on the market is different from market demand (it can be either smaller or larger than demand).

We distinguish invention (i.e. a novelty being considered to be introduced into practice) and innovation (an invention introduced into the production process). There are two ways in which firms search for inventions: autonomous, in-house research, and imitation of competitors. Public knowledge allows not only for imitation of competitors, but may also concern the research process (the arrow from public knowledge to autonomous research indicates this influence). From all inventions only a small fraction is selected to actually be used. Innovation may modernize current production but can also initiate new, radical way of production, i.e. by introducing essentially new technology. In general, each innovation may reduce unit costs, increase the productivity of capital, and improve product performance. However, it frequently happens that improvement of one factor is accompanied by deterioration of the two other. Firms therefore face the problem of balancing positive and negative factors of each invention. An invention will only become an innovation if the positive factors prevail.

In the model each firm may simultaneously produce products with different prices and different values of the characteristics, i.e., the firm may be a multi-unit operation. Different units of the same firm manufacture products by employing different sets of routines. Multi-unit firms exist because of searching activity. New technical or organizational solutions (i.e. a new set of routines) may be much better than the actual ones but immediate full modernization of production is not possible because of investment constraints on the firm. In such situations the firm continues production using the old routines and tries to open a new unit where production applying the new set of routines is started on a smaller scale. Subsequently, old production techniques may be slowly phased out.

Simulation of industry development is done in discrete time in four steps:

(1) Search for innovation (i.e., search for new sets of routines which potentially may replace the old set currently employed by a firm).
(2) Firms' decision making process (calculation and comparison of investment, production, net income, profit, and some other characteristics of development which may be attained by employing the old and the new sets of routines. Decisions of each firm on: (a) continuation of production by employing old routines or modernizing production, and (b) opening (or not) of new units).
(3) Entry of new firms.
(4) Selling process (market evaluation of the offered pool of products; calculation of firms' characteristics: production sold, shares in global production and global sales, total profits, profit rates, research funds, etc).

The search for innovation

The creative process is evolutionary by nature, and as such its description should be based on a proper understanding of the hereditary information (see Kwasnicki, 1996, Chapter 2). According to the tradition established by Schumpeter, and Nelson and Winter (1982), we use the term 'routine' to name the basic unit of the hereditary information of a firm. The set of routines applied by the firm is one of the basic characteristics describing it. In order to improve its position in the industry and in the market, each firm searches for new routines and new combinations of routines to reduce the unit costs of production, increase the productivity of capital, and improve the competitiveness of its products in the market. Nelson and Winter (1982, p. 14) define routines as 'regular and predictable behavioral patterns of firms' and include in this term such characteristics as 'technical routines for producing things ... procedures of hiring and firing, ordering new inventory, stepping up production of items in high demand, policies regarding investment, research and development, advertising, business strategies about product diversification and overseas investment'. A large part of research activity is also governed by routines. 'Routines govern choices as well as describe methods, and reflect the facts of management practice and organizational sociology as well as those of technology' (Winter, 1984).

Productivity of capital, unit costs of production, and characteristics of products manufactured by a firm depend on the routines employed by the firm (examples of the product characteristics are reliability, convenience, lifetime, safety of use, cost of use, quality and aesthetic value). The search activities of firms 'involve the manipulation and recombination of the actual technological and organizational ideas and skills associated with a particular economic context' (Winter, 1984), while the market decisions depend on the product characteristics and prices. We may speak about the existence of two spaces: the space of routines and the space of product characteristics.[1]

We assume that at time *t* a firm is characterized by a set of routines actually employed by the firm. There are two types of routines: *active*, that is, routines employed by this firm in its everyday practice, and *latent*, that is, routines which are stored by a firm but not actually applied. Latent routines may be included in the active set of routines at a future time. The set of routines is divided into separate subsets, called segments, consisting of similar routines employed by the firm in different domains of the firm's activity. Examples are segments relating to productive activity, managerial and organizational activity, marketing, and so on. In each segment, either active or latent routines may exist. The set of routines employed by a firm may evolve. There are four basic mechanisms for generating new sets of routines, namely: *mutation*, *recombination*, *transition* and *transposition.*

The probability of discovering a new routine (mutation) depends on the research funds allocated by the firm for autonomous research, that is, in-house development. It is assumed that routines mutate independently of each other. The scope of mutation also depends on funds allocated for in-house development.

The firm may also allocate some funds for gaining knowledge from other competing firms and try to imitate some routines employed by competitors (recombination). It is assumed that recombination may occur only between segments, not between individual routines, that is, a firm may gain knowledge about the whole domain of activity of another firm, for example, by licensing. A single routine may be transmitted (transition, see Figure 4) with some probability from firm to firm. It is assumed that after transition a routine belongs to the subset of latent

---

[1] In the model, the space of routines and the space of characteristics play model a role analogous to the space of genotypes and the space of phenotypes in biology. The existence of these two types of spaces is a general property of evolutionary processes. Probably the search spaces (that is, spaces of routines and spaces of genotypes) are discrete spaces in contrast to the evaluation spaces (that is, the space of characteristics and the space of phenotypes) which are continuous spaces. The dimension of the space of routines (space of genotypes) is much larger than the dimension of the space of characteristics (space of phenotypes).

routines. At any time a random transposition of a latent routine to the subset of active routines may occur (Figure 5). It is assumed that the probabilities of transition of a routine from one firm to another and the probabilities of transposition of a routine (from a latent to an active routine) are independent of R&D funds, and have the same constant value for all routines.

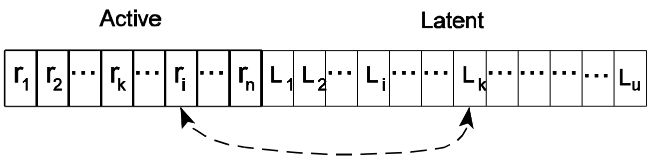

Figure 4. Routines transposition

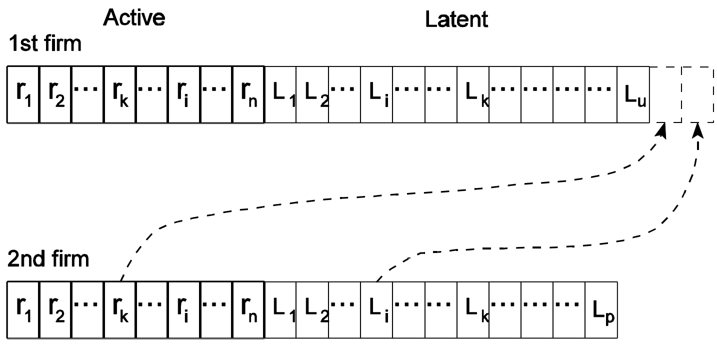

Figure 5. Routines transition

In general, the probability of transposition of a routine for any firm is rather small. But randomly, from time to time, the value of this probability may abruptly increase and very active processes of search for a new combination of routines are observed. This phenomenon is called recrudescence. Recrudescence is viewed as an intrinsic ability of a firm's research staff to search for original, radical innovations by employing daring, sometimes apparently insane, ideas. This ability is connected mainly with the personalities of the researchers and random factors play an essential role in the search for innovations by recrudescence, so the probability of recrudescence is not related to R&D funds allocated by a firm to 'normal' research. It is assumed that recrudescence is more probable in small firms than in large ones which spend huge quantities on R&D, although it is possible to assume that the probability of recrudescence does not depend on firm size.

As a rule, mutation, recombination and transposition on a normal level (that is, with low probabilities in long periods) are responsible for small improvements and, during the short periods of recrudescence, for the emergence of radical innovations.

Firm's decisions

It seems that one of the crucial problems of contemporary economics is to understand the process of decision-making. Herbert Simon states that 'the dynamics of the economic system depends critically on just how economic agents go about making their decisions, and no way has been found for discovering how they do this that avoids direct inquiry and observations of the process' (Simon, 1986, p. 38).

The background of the decision making procedure adopted in the model is presented in detail in Kwasnicki (1996). It is assumed that each firm predicts future development of the market (in terms of future average price and future average product competitiveness), and on the basis of its expectations on future market development and expected decisions of its competitors, each firm decides on price of its products, investment and quantity of production which it expects to sell on the market. Current investment capability and the possibility of borrowing are also considered by each firm.

The decision making procedure allows to model diversified situations faced by different firms, for example, the power of a small firm to influence the average price is much smaller than that of a large firm. So, small firms are, in general, 'price takers' in the sense that they assume that the future average price will be very close to the trend value, while large firms generally play the role of 'price leaders' or 'price makers'.

Price, production and investment are set by a firm in such a way that some objective function is maximized. Contrary to the neoclassical assumption it is not a maximization in the strict sense. The estimation of values of the objective function is not perfect and is made for the next year only. In other words, it is not a global, once and for all, optimization, but rather an iterative process with different adjustments taking place from year to year.

Different price-setting procedures (based on different objective functions and the markup rules) have been scrutinized, the results of which are presented in Kwasnicki and Kwasnicka (1992), and Kwasnicki (1996). In many simulation experiments, firms were allowed to select different price setting procedures. The results of these experiments suggest that firms applying the objective O_1 function (presented below) dominate on the market and in the long run supersede all others. This objective function has the following form:

$$
\begin{aligned}
O_1(t+1) &= (1-F_i)\,\frac{\Gamma_i(t+1)}{\Gamma(t)} + F_i\,\frac{Q_i^s(t+1)}{QS(t)}, \\
F_i &= a_4 \exp\left(-a_5\,\frac{Q_i^s(t+1)}{QS(t)}\right),
\end{aligned} \tag{1}
$$

where F_i is the magnitude coefficient (with values between 0 and 1), Q_i^s the supply of firm *i*, Γ_i the expected income of firm *i* at t +1 (defined by equation (2), below), *QS* is the global production of the industry in year *t* and Γ the global net income of all firms in year *t*. $\Gamma(t)$ and $QS(t)$ play the role of constants in equation (1) and ensure that the values of both terms in this equation are of the same order.

The expected income of firm *i* (Γ_i) and the expected profit of this firm (Π_i) are defined as

$$\Gamma_i = Q_i^s(t)\left(p_i(t) - V v(Q_i^s(t)) - \eta\right), \tag{2}$$

$$\Pi_i = \Gamma_i - K_i(t)(\rho + \delta), \tag{3}$$

where *V* is unit production costs, $v(Q_i^s)$ is the factor of unit production cost as a function of the scale of production (economies of scale), η is the constant production cost, $K_i(t)$ the capital needed to obtain the output $Q_i^s(t)$, ρ the normal rate of return and δ the physical capital depreciation rate (amortization).

The function O_1 expresses short- and long-term thinking of firms during the decision-making process (the first and second terms in equation (1), respectively). Plausible values for the parameters are $a_4 = 1$ and $a_5 = 5$, implying that the long run is much more important for survival and that firms apply a flexible strategy, i.e., the relative importance of short- and long-term components changes in the course of firm's development (the long-term one is much more important for small firms than for the big ones).

The decision-making procedure presented above, with the search for the 'optimal' price-setting procedure based on the objective function concept constructs a formal scheme for finding the proper value of the price and expected production to be sold on the market. Naturally this scheme is only an approximation of what is done by real decision-makers. They, of course, do not make such calculations and formal optimization from year to year, they rather think in the routine mode: 'My decisions should provide for the future prospects of the firm and also should allow income (or profit) to be maintained at some relatively high level'. Decisions on the future level of production and the future product price depend on the actual investment capabilities of the firm.

Entry

In each period (t, $t + 1$) a number of firms try to enter the market. Each entrant enters the market with assumed capital equal to *InitCapital* and with the initial price of its products equal to the predicted average price. The larger the concentration of the industry, the greater the number of potential entrants (that is, firms trying to enter the market). The value of *InitCapital* is selected in such a way that the initial share of an entrant is not larger than 0.5%.

In general, any firm may enter the market and if a firm's characteristics are unsatisfactory, then it is quickly eliminated (superseded) from the market. But because of the limited capacity of computer memory for simulations, a threshold for potential entrants is assumed. It is assumed that a firm enters the market only if the estimated value of objective O_1 of that firm is greater than an estimated average value of the objective O_1 in the industry. It may be expected that a similar (rational) threshold exists in real industrial processes.

Products competitiveness on the market

The productivity of capital, variable costs of production and product characteristics are the functions of routines employed by a firm (Figure 6). Each routine has multiple, pleiotropic effects, that is, may affect many characteristics of products, as well as productivity, and the variable costs of production. Similarly, the productivity of capital, unit costs of production and each characteristic of the product can be function of a number of routines (polygeneity). We assume that the transformation of the set of routines into the set of product characteristics is described by m functions F_d,

$$z_d = F_d(r), \quad d = 1, 2, 3, \ldots, m, \tag{4}$$

where z_d is the value of characteristic d, m the number of product characteristics, and r the set of routines. It is assumed also that the productivity of capital $A(r)$ and the unit cost of production $V(r)$ are also functions of firm's routines, where these functions are not firm specific and have the same form for all firms.

Attractiveness of the product on the market depends on the values of the product characteristics and its price. The competitiveness of products with characteristics z and price p is equal to

$$c(p, z) = \frac{q(z)}{p^{\alpha}}, \quad z = (z_1, z_2, z_3, \ldots, z_m), \tag{5}$$

where $q(z)$ is the technical competitiveness, z a vector of product characteristics, and α price elasticity.

In the presence of innovation, technical competitiveness varies according to the modification of routines made by each firm, or because of introducing essentially new routines. Technical competitiveness is an explicit function of product characteristics. As explained above, each routine does not influence the product's performance directly, but only indirectly through the influence on its characteristics. We assume the existence of a function q enabling calculation of technical competitiveness of products manufactured by different firms. We say that q describes the adaptive landscape in the space of product characteristics. In general, this function depends also on some external factors, varies in time, and is the result of co-evolution of many related industries. The shape of the adaptive landscape is dynamic, with many adaptive peaks of varying altitudes. In the course of time some adaptive peaks lose their relative importance, others become higher.

Due to the ongoing search process, at any moment each firm may find a number of alternative sets of routines. Let us denote by r the set of routines actually applied by a firm and by r^* an alternative set of routines. Each firm evaluates all potential sets of routines r^* as well as the old routines r by applying the decision-making procedure outlined in the former section. For each alternative set of routines the price, production, investment (including the modernization investment), and value of objective function are calculated. The decision of firm i on modernization (i.e., replacing the r routines by r^* routines) depends on the expected value of the firm's objective function and its investment capability. Modernization is undertaken if the maximum value of the objective function from all considered alternative sets of routines r^* is greater than the value of the objective function possible by continuing the actually applied routines r, and if the investment capability of the firm permits such modernization. If the investment capability does not allow modernization, then the firm:

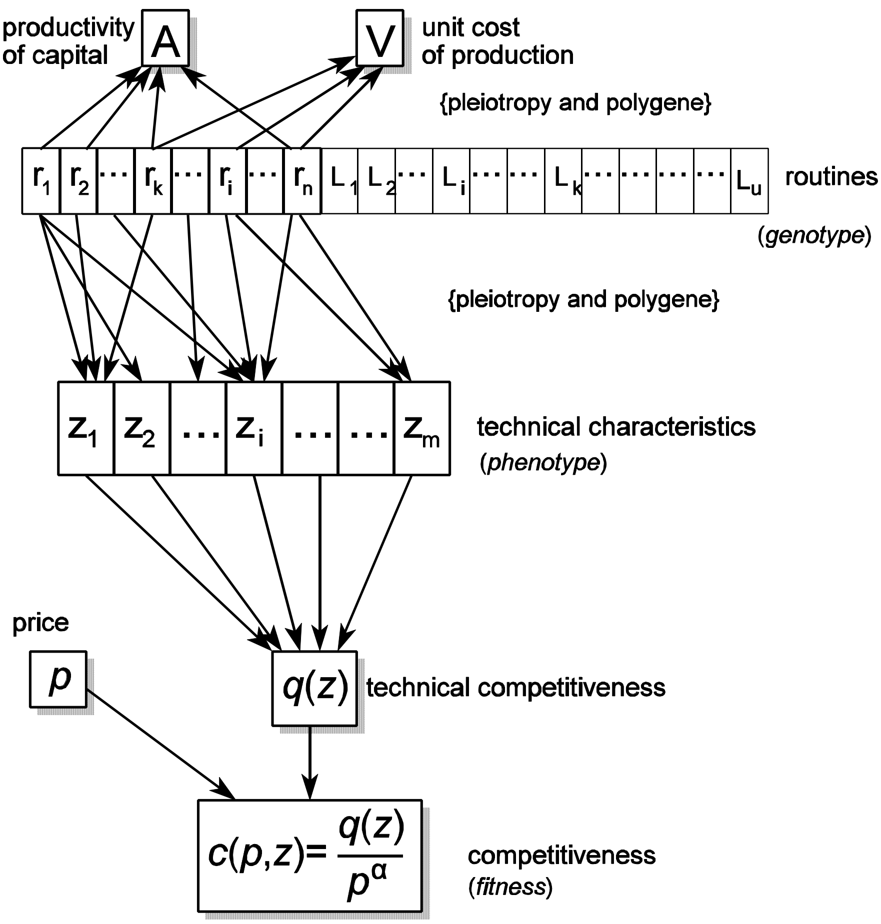

Figure 6. From routines to competitiveness, productivity of capital and unit cost of production

1. continues production employing the 'old' routines r, and
2. tries to open a new small unit where routines r^* are employed; production is started with an assumed value of capital equal to *InitCapital.*

To modernize production, extra investment is necessary. This 'modernization investment' depends on the discrepancy between the 'old' routines r and the 'new' routines r^*. For simplicity, it is assumed that modernization investment *IM* is a non-decreasing function of distance between the old routines *r* actually applied by a firm and the new set of routines r^*.

All products manufactured by the entrants and the firms existing in the previous period are put on the market and all other decisions are left to buyers; these decisions primarily depend on the relative values of competitiveness of all products offered, but quantities of products of each firm offered for sale are also taken into account. It is assumed that global demand $Q^d(t)$ for products potentially sold on a market is equal to an amount of money – $M(t)$ – which the market is inclined to spend on buying products offered for sale by the firms divided by the average price, $p(t)$, of the products offered by these firms,

$$Q^d(t) = \frac{M(t)}{p(t)}. \tag{6}$$

$M(t)$ is assumed to be equal to

$$M(t) = N \exp(\tilde{a} t)(p(t))^{\hat{a}} \tag{7}$$

where N is a parameter characterizing the initial market size, ã the growth rate of the market, and â the (average) price elasticity. The average price of all products offered for sale on the market is equal to

$$p(t) = \sum_i p_i(t) \frac{Q_i^s(t)}{Q^s(t)}. \tag{8}$$

where $Q^s(t)$ is global supply and is equal to

$$Q^s(t) = \sum_i Q_i^s(t). \tag{9}$$

Global production sold on the market is equal to the smaller value of demand $Q^d(t)$ and supply $Q^s(t)$,

$$QS(t) = \min\{Q^d(t),\ Q^s(t)\}. \tag{10}$$

The selection equation describing competition among firms (products) in the market has the following form (f_i is the market share of products manufactured by firm i):

$$f_i(t) = f_i(t-1)\frac{c_i(t)}{c(t)}, \tag{11}$$

where $c(t)$ is the average competitiveness of products offered for sale,

$$c(t) = \sum_i f_i(t-1) c_i(t). \tag{12}$$

This means that the share (f_i) of firm i in global output increases if the competitiveness of its products is higher than the average of all products present on the market, and decreases if the competitiveness is lower than the average. The rate of change is proportional to the difference between the competitiveness of products of firm i and average competitiveness.

Finally, the quantity of products potentially sold by firm i (i.e., the demand for products of firm i) is equal to

$$Q_i^d(t) = QS(t) f_i(t). \tag{13}$$

The above equations are valid if the production offered by the firms exactly fits the demand of the market. This is a very rare situation and therefore these equations have to be adjusted to states of discrepancy between global demand and global production, and discrepancy between the demand for products of a specific firm and the production offered by this firm. The details of this adjustment process is presented in Kwasnicki (1996). Equation (13) describes the market demand for products of firm *i* offered at a price $p_i(t)$ and with competitiveness $c_i(t)$. In general, however, the supply of firm *i* is different from the specific demand for its products. The realization of the demand for products of firm *i* does not depend only on these two values of demand and supply, but on the whole pool of products offered for sale on the market. The alignment of supply and demand of all firms present on the market is an adaptive process performed in a highly iterative and interactive mode between sellers and buyers. In our model, we simulate the iterative alignment of supply and demand in a two-stage process in which a part of the demand is fulfilled in the first stage, and the rest of the demand is, if possible, fulfilled in the second stage. If there is no global oversupply of production, then in the first stage of the supply–demand alignment process all demand for production of specific firms, wherever possible, is fulfilled, but there is still the shortfall in production of firms which underestimated demand for their products. This part of demand is fulfilled in the second stage of the supply–demand alignment process. At this stage, the products of the firms which produce more than the specific demand are sold to replace the shortfall in production by the firms which underestimated the demand for their products.

The supply–demand alignment process is slightly different if a global oversupply of production occurs. It seems reasonable to assume that in such a case the production of each firm sold on the market is divided into (1) the production bought as the outcome of the competitive process (as described by equations 15 and 17), and (2) the production bought as the outcome of a non-competitive process. The latter part of production does not depend directly on product competitiveness but primarily depends on the volume of production offered for sale, i.e., random factors play a much more important role in the choice of relevant products to be bought within this part of the production. In general, the division of production of each firm into these two parts depends on the value of global oversupply. The higher oversupply, the larger is the part of production of each firm which is sold on the basis of non-competitive preferences.

Usually global oversupply, if it occurs, is small, so the major part of production is distributed under the influence of competitive mechanisms and only a small part is distributed as a result of non-competitive distribution. But to clarify the necessity of distinguishing the two proposed stages of the selling–buying process let us consider the following, albeit artificial, situation. Except for one firm, the production of all other firms exactly meets the demand for their products. The a-typical firm produces much more than the demand for its products. It could be assumed that the production sold by all firms is exactly equal to the specific demands for their products, which is equivalent to the assumption that the volume of overproduction of the a-typical firm does not influence the behaviour of the market. In an extreme case, we may imagine that the volume of production of the a-typical firm is infinite and the rest of the firms continue to produce exactly what is demanded. Does this mean that the excessive production would go unnoticed by the buyers and that they would remain loyal to firms producing exactly what is demanded? It seems a more adequate description requires the incorporation of the assumption that the future distribution of products sold on the market depends on the level of overproduction of all firms, and particularly the level of overproduction of the a-typical firm. And it seems that in the case of the overproduction of one firm its share in the global production sold will increase at the expense of all firms producing exactly what is demanded. In the extreme case, when overproduction of the a-typical firm tends to infinity, the only products sold on the market belong to that firm, and the shares of all other firms will be zero. But it does not mean that producing more than is demanded is an advantageous strategy for the firm and that it is an effective weapon to eliminate the competitors. In fact, the bulk of overproduction is not sold on the market and is lost by the firm. In effect the a-typical firm's profit is much smaller than expected, or even may be negative. After some time the firm's development stop and in the end it will be eliminated from the market.