

contribution to such a firm-oriented theory is found in Penrose's *The Theory of the Growth of the Firm* (1959/80). From the viewpoint of the present book such studies are concerned with ontogenetic evolution (developmental processes of individuals) rather than the kind of evolution with which we are mainly concerned, namely phylogenetic evolution or evolution of the species, which must include an explicit population level.<sup>1</sup> Both types of studies are, of course, important, but there is a trade-off. If we focus on the detailed behaviour of the individual decision-maker or the complex firm, as Simon and other behaviouralists do, then attention is drawn away from the overall changes at the population level and the competitive processes which drive these changes. However, their studies contribute to the understanding of problem complexity as part of the 'origin of predictable behaviour' (Heiner, 1983; 1989) and this contribution is a necessary precondition for the development of the new evolutionary economics.

## **4.2. The pioneering work of Nelson and Winter**

### *4.2.1. An evolutionary synthesis*

Nelson and Winter presented their versions and interpretations of what I call Artificial Economic Evolution in a series of papers (from Nelson and Winter, 1973; 1974 to Winter, 1984/91) and in the related book, *An Evolutionary Theory of Economic Change* (1982). Through this work they demonstrated the possibility of overcoming the basic difficulty in studying evolutionary processes, namely the need to combine elements in a complex manner which are normally considered as belonging to quite different areas of investigation. Such a combination presupposes two opposing qualifications: an ability to cope with a wide diversity of elements and an ability to cut out the details and integrate the elements into an initially crude conception of an evolutionary process. Only in this way is it possible to create a framework which makes sense of the processes of transmission and variety-creation. The computer helps to organise this exercise including the last steps of synthesis since 'the simulation format does impose its own constructive discipline in the modeling of dynamic systems: the program must contain a complete specification of how the system state at  $t + 1$  depends on that at  $t$  and on exogenous factors, or it will not run.' (Nelson and Winter, 1982, 208 f.)

The evolutionary models created through the collaboration of Nelson and Winter build on their previous individual scientific works. Before their joint work, Winter (1964; 1971/93) had already made important critiques of the Alchian—Friedman selection argument for profit maximisation (see section 1.1.3) while Nelson had been working on the economics of invention, innovation and technical change (Nelson, 1959a; 1959b; 1968). Through their common research endeavour they made an evolutionary synthesis by integrating ideas about:

1. Behavioural patterns and their transmission.
2. Creation of new behavioural patterns.
3. Different types of selection mechanisms.

More specifically, we may say that they combined:

1. Simon's work on rules and satisficing behaviour.
2. Nelson's and other 'Schumpeterian' work on invention and innovation.
3. Alchian's and Winter's work on 'natural selection'.<sup>2</sup>

In the creation of the evolutionary synthesis there is little doubt that the contribution of Simon (and Cyert and March) was of crucial importance.<sup>3</sup> However, the evolutionary synthesis is a clear example that the whole is more than its constituent parts. Furthermore, we see that the elements were reshaped to fit into their new place in the evolutionary synthesis. Therefore, it is appropriate to present the models as if they were wholly created through Nelson and Winter's joint work even if they are heavily indebted to several sources.

Nelson and Winter's evolutionary models are based on the postulate that it is possible to specify the space in which innovative search takes place as well as the way the actual search process takes place. In other words, we postulate a degree of stochastic predictability of most innovative activities which may allow the formulation of 'laws of succession', of course in probabilistic terms and subject to *ceteris paribus* clauses. Behind the 'laws' are firms' and financial organisations' rules of searching and decision-making which are in many ways bound to their present state. The search for new rules often starts with problems arising from existing rules, and the result of the search will be evaluated by comparison with these rules. This predictable aspect of economic change may be seen as a result of bounded rationality leading to localised search in the space of (technological and marketing) alternatives. Here distance is measured in terms of search costs, and there is increasing uncertainty about the precise characteristics of alternatives. What the firm applies as a relatively stable solution will, at best, express a temporary local optimum.

Generally, we try to imagine the state of a firm at period  $t$  with respect to, e.g., physical capital, productivity, product characteristics (in industries with heterogeneous products), etc. Together with output rules and functions of factor supply and final demand, this state determines the firm's competitiveness *vis-à-vis* its similarly described competitors and thus its profitability in period  $t$ . The firm's state in the next period,  $t + 1$ , is determined by its (simplified) investment rules and by its search rules (and thus search costs) together with the (assumed) probabilities of finding new rules in the space of alternatives. A newly found alternative will only be included into the new state of the firm if it is judged to increase expected profitability.

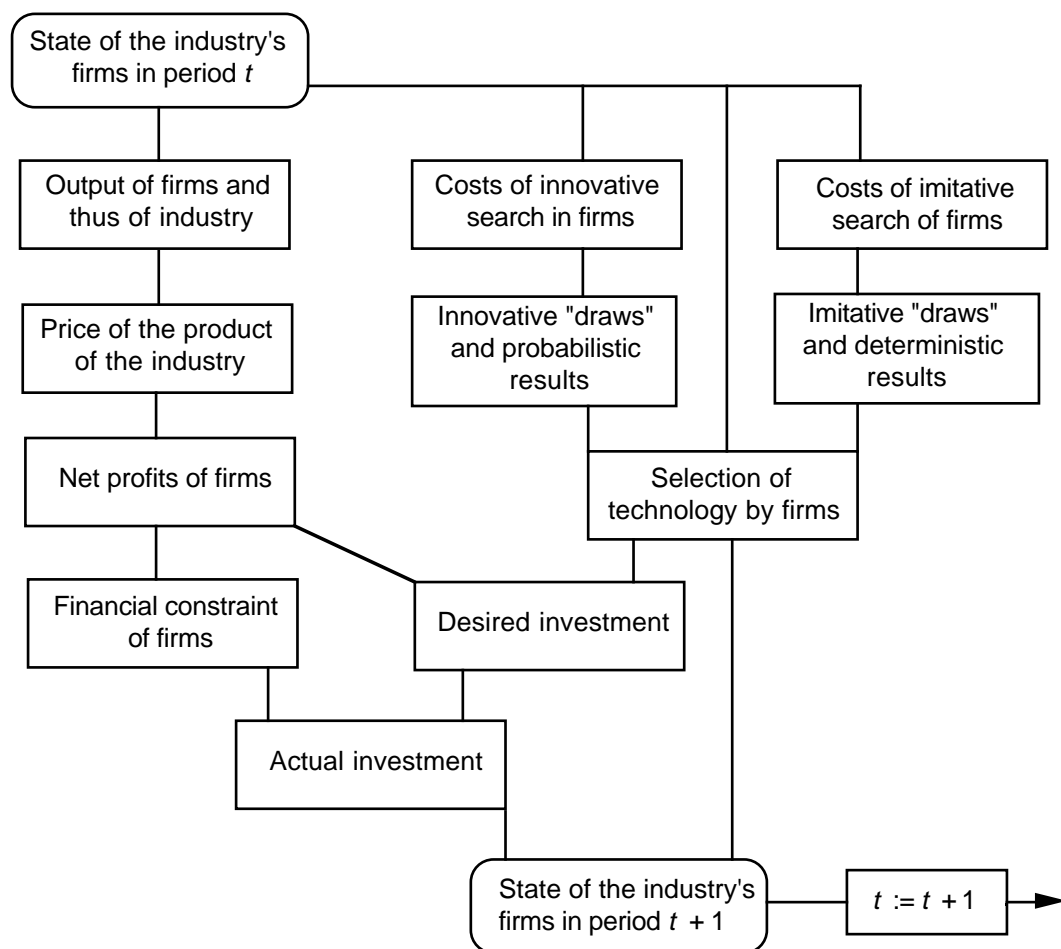
This modelling strategy may be summarised in the following way:

1. Define the minimum environmental characteristics, including input and output conditions as well as the spaces in which search for new rules is performed.
2. Define the state of the industry at time  $t$  as a list of firm states which include physical and informational characteristics as well as behavioural rules and meta-rules.
3. Calculate by means of (1) and (2) the activities of the industry in period  $t$  as well as the resultant state variables (including possible changes of rules) which characterise the system at the start of period  $t + 1$ .
4. Make similar calculations for a series of periods and study the evolution of the application of different rules as well as other characteristics of the industry (economy).

By accepting such kinds of elements in their model-makers' tool-kit, Nelson and Winter are imposing upon themselves a certain conception of the evolutionary process. First of all, they apply a population perspective. An 'industry' or an 'economy' is seen as a taxonomic class incorporating a certain degree of variety of processes and/or products; but the variants must, in principle, be transferable between the different firms. This also implies a certain similarity of the search spaces of the firms, although there may be major differences with respect to the 'distance' to different sources of knowledge. The reader should be aware that the empirical relevance of the whole argument is heavily dependent upon the possibility of defining a level of aggregation and a related taxonomy which are not arbitrary constructs of (national) statistical services but which instead reflect important similarities and differences with respect to the factors of the evolutionary process. Second, the name of the game is variety-creation and variety-selection within a given economic pattern. In other words, Nelson and Winter emphasise change which follows 'natural trajectories' within given 'technological regimes' (Nelson and Winter, 1982, 258-262) or 'technological paradigms' (Dosi, 1982) rather than radical change. The latter is suggested in contrast to their models rather than within their models. Third, 'a vast array of particular models can be constructed within the broad limits of the theoretical schema' but the 'enormous generality' of the schema cannot be exploited immediately (Nelson and Winter, 1982, 19 f.). To obtain real understanding about how to handle their powerful family of models, Nelson and Winter prefer to concentrate on 'very simple examples' and to 'distinguish sharply between the power and generality of the theoretical ideas we employ and the much more limited results that our specific efforts have yielded thus far.' (pp. 20 f.)

4.2.2. *Typical Nelson-and-Winter simulation models*

In their attempts to exploit their highly general modelling scheme, Nelson and Winter have developed several generic and specific types of models.<sup>4</sup> To grasp their basic ideas, we have to concentrate on one central example. It is their most developed and documented model type (see Nelson and Winter, 1982, chs. 9, 12; Winter, 1984/91) which deals with the evolution of the production techniques and other behavioural rules of an industry producing a homogeneous product. This species of model may be considered as Nelson and Winter's major contribution to Artificial Economic Evolution and it includes the elements of decision rules, search and selection.<sup>5</sup>



**Figure 4.1.** The computational structure<sup>6</sup> of simple simulation models of Nelson and Winter.<sup>7</sup>

By concentrating on this model type we also have the opportunity of applying some techniques like flow charts and an algorithmically oriented notation (see the appendix on the latter issue). These techniques may be more helpful in reflecting upon simulation models than the usual kind of mathematical notation. The latter method of exposition is used by Nelson and Winter and practically everybody else. However, we occasionally see

an uncontrolled application of computerese which illustrates the problem (see Nelson and Winter, 1978, 544-547).

Figure 4.1 describes the computational structure of the Nelson-and-Winter model variant on which we shall concentrate in the following. Like all the other Nelson-and-Winter models, it determines (probabilistically) what happens in each period. This period has inherited a state of the industry from the former period. The state is defined in terms of the size of the physical capital stock and the productivity of capital of each firm.

The computational steps of the figure describe how the state of the industry in the next period is found when the state (capital stock and productivity) of the present period is given.

First, the left column of the figure shows a simple short-run system, i.e., a simplified economic process in the industry whereby output, price, profits and financial constraints of firms are found.

1. Output of each firm is decided by simple capacity utilisation *rules* of firms, e.g., full capacity utilisation.
2. Output of the industry is found by simple aggregation.
3. The aggregate output of the industry faces exogenously given demand conditions, e.g., a conventional downward-sloping market demand curve. This gives the market-clearing price per unit of output.
4. For each firm we calculate the turnover and then find the net profit by deducting capital depreciation, variable production costs and search costs (which are, e.g., all given per unit of physical capital).

Second, the upper parts of the middle and right columns of figure 4.1 show the processes whereby new production techniques are found and productivity is changed. In the particular model under consideration firms are always involved in a search for better production techniques. Because of this, they explore a space of possible production routines which are defined in terms of capital productivity.<sup>8</sup> Their search costs are defined by fixed relationships to their capital stock and are of two types: innovative search and imitative search. We shall start with the simpler case of imitation (even if innovation is logically prior to imitation).

1. The effort and costs to imitate the techniques of other firms are given by the firms' *rules* of determining the size of the budget of imitative search (which may also be classified as imitative R&D). In the present Nelson-and-Winter model the rule is the same in all firms, namely to use a fixed amount of imitative search costs per unit of capital.
2. Because of its imitative search effort, each firm gets access to a 'lottery'. Its probability of obtaining a 'draw', i.e. to draw a ticket from the lottery,<sup>9</sup> is proportionate to its imitative search costs but

is otherwise determined by exogenous factors (the difficulty of imitation in the particular industry).

3. A 'draw' means that the firm gets access to the best-practice technique and thus the highest productivity level obtained by any firm in the period.
4. The firm's *rule* concerning the costs of innovative search (innovative R&D) is also to spend a fixed amount on innovative search per unit of capital.
5. The firm's chance of getting a 'draw' (a successful innovation) in the innovative 'lottery' is proportionate to its innovative costs as well as to the exogenously given character of technical change in the industry. The technique found by a 'draw' depends on exogenously given probability distributions. To give an impression of such distributions we may consider two major types (Nelson and Winter, 1982, 211 f., 283). The simplest case is a 'science based' industry where the probability distribution is only dependent on exogenous factors. In the case of an industry characterised by production-near 'learning processes' and thus 'cumulative technology', the value of a 'draw' is most likely to be near the firm's present technology (localised search).
6. The attempts to improve productivity end with a comparison between the productivities obtainable by the technique inherited from the last period and the techniques which may be found by imitative and innovative search. The technique with the highest productivity is chosen.
7. If the technique is changed, it will determine productivity of the next period (disembodied technical change). We thus have the state of technique (production routines) for period  $t + 1$ .

Third, the lower parts of figure 4.1 are concerned with the investment decision.

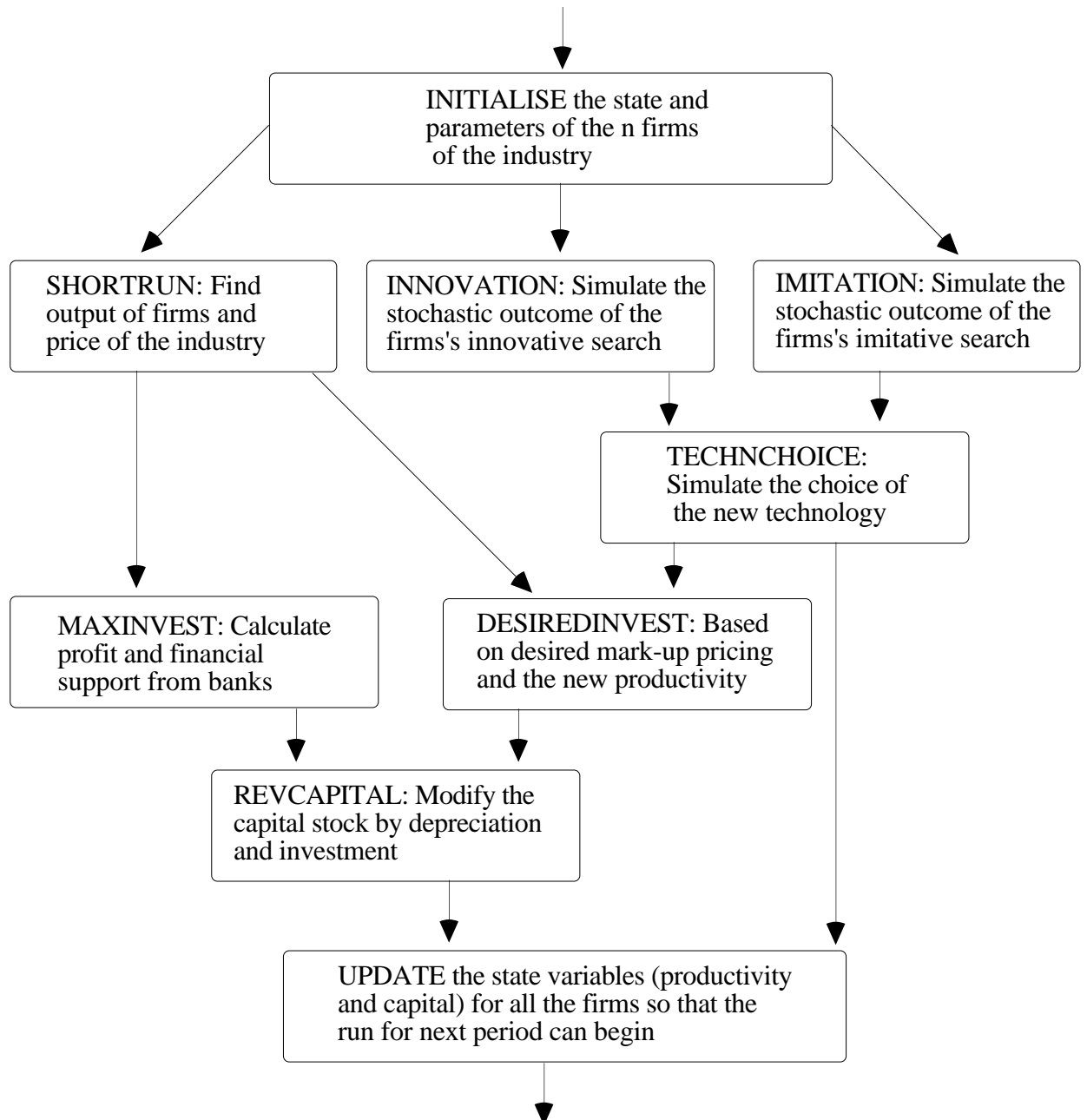
1. The only way to reduce productive capacity is through the process of physical depreciation, but this is not depicted by the figure.
2. The firm's gross investment function is bounded below by the non-negativity condition and above by the financial constraint. The financial constraint is determined by the net profit which is increased by external financing in some ratio to net profit.<sup>10</sup> This allows a primitive treatment of the role of banks' rules in the evolutionary process (see Nelson and Winter, 1982, 291 ff.).
3. The firm's desired net investment depends on a) the ratio of the price of the period to unit costs of the next period (taking into account productivity change), b) a target mark-up factor which is an increasing function of the firm's market share. The desired net investment responds positively to the price/cost ratio and negatively to the market share.

4. Actual investment depends, of course, on desired investment as well as investment constraints.
5. The investment process has no time-lags. The adjusted physical capital stock is available to the industry's firms in period  $t + 1$ . By multiplying the capital stock with the new level of productivity, we have the production capacity of the firms of the industry in period  $t + 1$ .

And so the computation goes on and on for  $t + 1, t + 2, \dots$

This exposition of the basic computational structure of the typical Nelson-and-Winter model does not specify fully the simulation programs. On the contrary, a large number of decisions has to be made before we have a functioning computer program and/or a full mathematical specification of the Markov chain. However, the exposition has more or less followed the rules of structured programming (Dahl *et al.*, 1972) and may later open up for modular programming (Wirth, 1982).<sup>11</sup> This means that we may apply a top-down approach to programming where the computation is gradually decomposed in more and more detailed tasks. Furthermore, it means that most of the 'boxes' in figure 4.1 may to some extent function as modules with relatively simple interfaces *vis-à-vis* other 'boxes'. This means that each module can be specified in relative isolation from the other modules. More importantly: a primitive version of a module can later be exchanged with a more sophisticated version; an old version of a module which reflects one hypothesis can be exchanged with a new version which reflects another hypothesis.

Figure 4.2 (see next page) serves to emphasise this structured and more or less modular design as well as to depict the structure of the above comments on figure 4.1. In the new figure we emphasise the need to make a procedure INITIALISE which defines the data structures for the process of computation. This does not only include the state variables (the initial capital stock and productivity of each of the  $n$  firms of the industry) but also the parameters which, e.g., specify the behavioural response of the firms and the demand side of the market. The SHORTRUN procedure defines the market process based on given behavioural routines, given capital stocks and productivities, and a specification of the demand side of the market. A small set of procedures (INNOVATION, IMITATION and TECHNCHOICE) defines how the firms try to exploit the technological search space as well as each other's capabilities and determines the resultant productivity of each of the firms. Similarly, a small set of procedures (MAXINVEST, DESIREDINVEST and REVCAPITAL) defines the investment and depreciation process of firms. Taken together the procedures deliver inputs to the master procedure UPDATE which modifies the state variables after each period of computations.



**Figure 4.2.** The basic procedures of typical Nelson-and-Winter models

Figures 4.1 and 4.2 can serve as direct starting points for further discussions and for the programming exercises which are reported in the appendix to this book. Such an immediate jump to the details of programming is, however, not advisable. It can easily lead to idiosyncratic specifications of firm and market behaviour which means that the simulation results are of little or no value. It may also serve to block the possibility of exploring the mathematical properties of the computational system. For such reasons there is a need to make a more formal specification of the model.

### 4.3. A formal version of the computational structure of typical Nelson-and-Winter models

Before the Nelson-and-Winter simulation models were designed, Winter (1964; 1971/93) was engaged in theoretical modelling and this work supplies much of what is needed for a formal specification of the later programming exercises. After much of the common work was performed, Winter (1984/91; 1986) also made presentations of the Nelson-and-Winter models which provide the best available specifications (but we also find specifications in, e.g., Nelson and Winter, 1978; 1982).

However, even if this material is available, there is a need to rethink the computational structure of typical Nelson-and-Winter models for two reasons. First, such a specification may serve as a common frame of reference for evolutionary-economic research. Such a reference is very important as a means of providing concerted action rather than Babylonian confusion.<sup>12</sup> Second, the algorithmic orientation of the specification may serve to ease the development of Artificial Economic Evolution. Third, formalisation of a computational process may serve to create an interface between researchers working with on the one hand formal-theoretical analysis and on the other hand numerical computer simulation.

Even if the rough description of the basic structure of the most important type of Nelson-and-Winter simulation models can be expressed by mathematical equations, I prefer to apply an algorithmic notation (see A.1.1) which emphasises the relationship between formal specifications and programming language specifications (some of which are listed in A.2 and A.3). Three major characteristics should be mentioned. First, the specification is made in the form of a series 'assignment statements' (':= ' or '← ') which denote change of the computer variables in successive order (from 4.1 to 4.22).<sup>13</sup> The creation of data structures and the modification of state variables are sometimes specified as 'definition statements' ('≡'). Second, the specifications are made in terms of a language which is able to formulate *all* possible computations (according to the Church-Turing thesis). It uses sequences of statements (do A;do B;...), iteration (while < condition > do A;) and selection (if < condition > then A;). The power of the notation will not be seen much in most of the following specifications since it concentrates on fairly simple issues. However, the computer procedures in the appendix use practically the same notation, and here it is clearly needed even if only simple procedures have been recorded. Third, variables are named with time subscripts. This does not mean that the computer (or the firm) allocates new memory space for all these variables. Instead a new value is assigned to an old variable. The subscripts make it easier to distinguish between different types of variables (scalars and vectors), and they are necessary for mathematical treatment.

In making the formal description of the simple Nelson-and-Winter model, it has been natural to spell out several details which are implicit in

Nelson and Winter's accounts (and especially their poorly documented book).<sup>14</sup> However, it must be emphasised that all descriptions operate at a certain level of abstraction which leaves many kinds of detail open until the phase of implementation (appendix). In the present case many important decisions about the specification of central functions of the Nelson-and-Winter model are left out (except for occasional remarks and footnotes). Of special importance are the problems relating to the stochastic functions describing the processes of innovation<sup>15</sup> and imitation. Actually, it is these functions which to a large extent determine the outcome of the subsequent simulations. In any full treatment of the Nelson-and-Winter models these functions should be spelled out and discussed. The goal of the present exercise is, however, to prepare the ground for a discussion of Schumpeter's work in a modern evolutionary-economic context. This purpose suggests a condensed exposition which, e.g., has to leave out the controversy with textbook neoclassicism which occupies too much of the space in Nelson and Winter's writings.<sup>16</sup>

#### 4.3.1. *Inheritance from period $t - 1$*

We have an industry composed of firms producing a homogeneous product by means of homogeneous physical capital where the productivity is determined by techniques. To describe the state of the computation between the periods we have

$$\mathbf{K}_t \equiv (K_{1t}, \dots, K_{it}, \dots, K_{nt});$$

$$\mathbf{A}_t \equiv (A_{1t}, \dots, A_{it}, \dots, A_{nt});$$

where  $\mathbf{K}_t$  and  $\mathbf{A}_t$  are arrays (vectors) describing the state of the system in the beginning of period  $t$ ;  $K_{it}$  is capital stock of firm  $i$  at time  $t$ ;  $n$  is the fixed number of firms in the industry;  $A_{it}$  is productivity of capital (the output/capital ratio).

#### 4.3.2. *Short-run behaviour*

Given the state of a firm, we compute its output which is simply determined by its capital productivity and its capital stock (4.1); at the same time we have the total production of the industry (4.2). All output is sold but its price is determined by the (simplistic) demand conditions which take price to be determined by the output of the industry in the period (4.3). We may now find the sales of each firm (4.4) as well as production costs (4.5) and the unconventional variables: innovative and imitative search costs ((4.6), (4.7)). Finally, we calculate the net return (4.8). In formal terms this series of computations can be described as:

$$Q_{it} := A_{it}K_{it}; \tag{4.1}$$

$$Q_t := \sum_i Q_{it}; \quad (4.2)$$

$$P_t := D(Q_t); \quad (4.3)$$

$$S_{it} := P_t Q_{it}; \quad (4.4)$$

$$C_{it} := cK_{it}; \quad (4.5)$$

$$R_{it}^n := r^n K_{it}; \quad (4.6)$$

$$R_{it}^m := r^m K_{it}; \quad (4.7)$$

$$Z_{it} := S_{it} - (C_{it} + R_{it}^m + R_{it}^n); \quad (4.8)$$

where  $Q_{it}$  is quantity of output of firm  $i$  at time  $t$ ;  $Q_t$  is aggregate output of the industry;  $P_t$  is price per unit of output;  $D(\ )$  is the demand-price function for the output;  $S_{it}$  is total sales;  $c$  is production cost per unit of capital (including capital rental);<sup>17</sup>  $C_{it}$  is total production cost for firm  $i$  in period  $t$ ;  $r^n$  is cost of innovative activities per unit of capital;  $R_{it}^n$  is total innovation cost;  $r^m$  is cost of imitative activities per unit of capital;  $R_{it}^m$  is total imitation cost;  $Z_{it}$  is net return or economic profit.

#### 4.3.3. Productivity change through innovation and imitation

The computations of productivity change are central to the results of the Nelson-and-Winter simulations of evolutionary processes. However, this part of the model is relatively poorly documented by Nelson and Winter. It includes two broadly similar components. First, we have innovation: the innovative search effort determines the probability of finding an innovation (4.9), while a complex probability function<sup>18</sup> determines whether search will be successful in period  $t$  (4.10). The concrete outcome of the successful search is determined by another sampling from a distribution of technological opportunities (4.11). Second, we have imitative search whose success or failure are determined in a similar way as in the case of innovation ((4.12), (4.13)). However, the outcome of successful imitation is much simpler: it implies an access to the best-practice technique of the industry (4.14). Finally, the firm chooses between the existing technique and the new possibilities (4.15). Formally:

$$\gamma_{it}^n := d^n R_{it}^n; \quad (4.9)$$

$$\theta_{it}^n := \theta^n(\gamma_{it}^n); \quad (4.10)$$

$$\left. \begin{array}{l} \text{if } \theta_{it}^n = \text{true} \\ \text{then } A_{it}^n := \psi(A^{\text{init}}, \varphi, t, A_{it}) \\ \text{else } A_{it}^n := A_{it}; \end{array} \right\}^{19} \quad (4.11)$$

$$\gamma_{it}^m := d^m R_{it}^m; \quad (4.12)$$

$$\theta_{it}^m := \theta^m(\gamma_{it}^m); \quad (4.13)$$

$$\left. \begin{array}{l} \text{if } \theta_{it}^m = \text{true} \\ \text{then } A_{it}^m := \max[A_{1t}, \dots, A_{it}, \dots, A_{nt}] \\ \text{else } A_{it}^m := A_{it}; \end{array} \right\} \quad (4.14)$$

$$A_{i,t+1} := \max[A_{it}, A_{it}^m, A_{it}^n]; \quad (4.15)$$

where  $\gamma_{it}^n$  is the probability of getting a ‘draw’ in the lottery of innovation which depends on the similar probability per unit of search costs,  $d^n$ ;  $\theta_{it}^n$  is a variable which is true in case of an innovative ‘draw’ and otherwise false;  $\theta^n(\ )$  is the probabilistic function which determines whether a ‘draw’ will occur in period  $t$ ;  $A_{it}^n$  is the outcome of innovative activities;  $\psi(\ )$  is the probabilistic function which determines the outcome of an innovative ‘draw’;  $A^{\text{init}}$  is the initial value and  $\varphi$  is an expression of the time-dependence of the mean of the log-normally distributed  $A_{it}^n$ ;  $\gamma_{it}^m$ ,  $d^m$  and  $A_{it}^m$  are the expressions for imitative activities which correspond to the similar expressions for the process of innovation;  $\max[\ ]$  is the function choosing the best among the available production techniques.

#### 4.3.4. Change in physical capital<sup>20</sup>

The sequence of computations about the change in physical capital is relatively straightforward. The financial constraint (4.17) is calculated on the basis of the profitability of the firm (4.16) as well as bankers’ financial rules. The desired investment (4.20) depends on the market share of the firm (4.18), the mark-up factor (4.19) and the depreciation rate. Actual investment implies a constrained fulfilment of desires (4.21) and the new capital stock is found by taking into account the old capital stock and depreciation (4.22). Formally:

$$\pi_{it} := \frac{Z_{it}}{K_{it}}; \quad (4.16)$$

$$I_{it}^{\max} := G(\pi_{it}, b) \cdot K_{it};^{21} \quad (4.17)$$

$$\mu_{it} := \frac{Q_{it}}{Q_t}; \quad (4.18)$$

$$\rho_{it} := \frac{P_t}{c/A_{i,t+1}}; \quad (4.19)$$

$$I_{it}^{\text{des}} := H(\rho_{it}, \mu_{it}, \delta) \cdot K_{it}; \quad (4.20)$$

$$I_{it} := \max[0, \min[I_{it}^{\text{des}}, I_{it}^{\max}]]; \quad (4.21)$$

$$K_{i,t+1} := I_{it} + (1 - \delta)K_{it};^{22} \quad (4.22)$$

where  $\pi_{it}$  is economic profit per unit of capital;  $I_{it}^{\max}$  is maximum gross investment;  $G(\ )$  is the function which determines maximum gross investment per unit of capital;  $b$  is the ratio of external financing to economic profit;  $\delta$  is the physical depreciation rate per unit of capital;  $\mu_{it}$  is the market share;  $\rho_{it}$  is the price/unitcost ratio;  $I_{it}^{\text{des}}$  is desired gross investment;  $H(\ )$  is the function which determines desired gross investment per unit of capital;  $I_{it}$  is gross investment;  $\max[ \ ]$  and  $\min[ \ ]$  are the well-known functions which take the maximal and the minimal of their arguments.

#### 4.3.5. State of the system at the beginning of period $t + 1$

At the end of the computations performed for period  $t$  we have the updated state of the system organised as

$$\mathbf{K}_{t+1} \equiv (K_{1,t+1}, \dots, K_{i,t+1}, \dots, K_{n,t+1});$$

$$\mathbf{A}_{t+1} \equiv (A_{1,t+1}, \dots, A_{i,t+1}, \dots, A_{n,t+1});$$

To prepare the system for the next round of computations we change the arrays of state variables as well as the time counter:

$$\mathbf{K}_t := \mathbf{K}_{t+1};$$

$$\mathbf{A}_t := \mathbf{A}_{t+1};$$

$$t := t + 1;$$

We may now go to section 4.3.2 and perform computations (4.1)–(4.22) once more.

#### *4.3.6. Implementing the formal specifications*

The thesis underlying the present report is that programming languages and concrete programs are important for economic-evolutionary analysis for two reasons. First and most obviously, the programming approach allows the researcher to create artificial worlds in which he can launch and study well-defined but highly complex ‘evolutionary’ processes. In some cases, the researcher may gain his first rough concept of evolution through such an interaction with a computer system. Second, the researcher may use the notation of a programming language as well as the results of computer simulations as a means of communication with other researchers. The programming notation may give clarity and power to the communication and in the future this may be of major importance for the development of evolutionary analysis.

The sceptical economist may ask whether attempts to clarify and imitate evolutionary processes by means of computer simulation really make any difference. What can we possibly learn from simulation that we did not know already? This question is based on the twin propositions that a computer does what it is programmed to do and that a simulation cannot be better than its underlying assumptions (‘garbage in, garbage out’). The apparently obvious conclusion is that we cannot learn anything: computers and simulations are just means of expressing given ideas (like the above specifications).

While the propositions are correct, they do not lead to the conclusion that computer-implementable models are largely irrelevant. First, we have the well-known fact that it is often quite difficult to discover the consequences of a correct set of propositions; here simulation will often help us. Second, and more importantly, we have the effect of trying to express poorly understood processes in a form which is implementable on a digital computer. In cognitive science we see how the long-term stalemate in the verbal modelling of cognitive phenomena has been overcome and is followed by a creative (and partly confusing) scientific boom which is directly and indirectly related to Artificial Intelligence.<sup>23</sup> Here we see the crucial importance of simple standard cases (like chess-playing and theorem proving), core algorithms and data structures (lists, production systems, heuristic search, learning, etc.), and specialised programming languages (LISP, PROLOG, etc.).<sup>24</sup> Similarly, we may expect that Artificial Evolution will create its standard cases, algorithms, data structures and programming languages.<sup>25</sup>

Against this background and when we consider how to program Nelson-and-Winter models, we may say that the above specification is very incomplete. After such a general specification, the next task is to program the data structures and implement the procedures (appendix).

Here a large number of new problems of major importance for the evolutionary process emerge. Finally, we come to the concrete 'running' of the procedures. In this step we specify the maximum number of firms and periods to be studied. We also call the initialisation procedure which defines the initial values of parameters and some variables. At this point it is, e.g., possible to specify

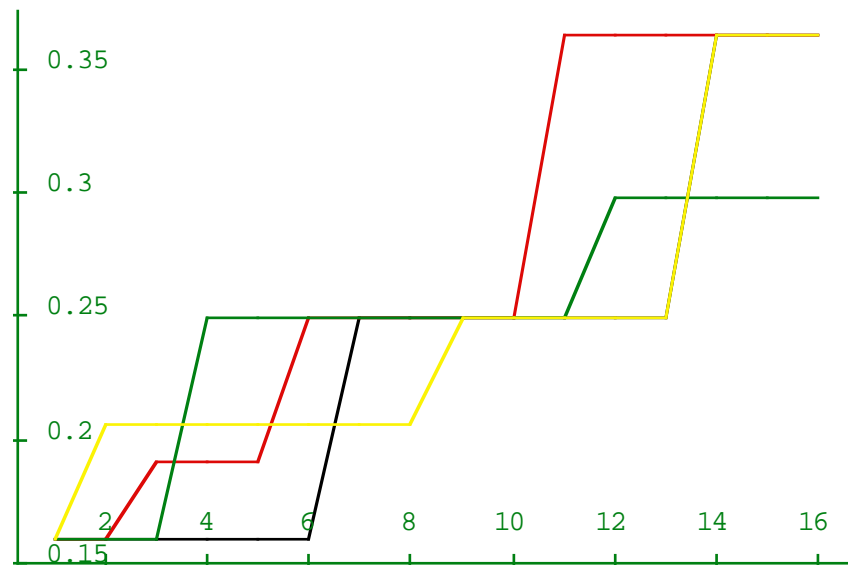
1. Whether a standard search space should be used or whether a new search space with a certain number of points (and, perhaps, a certain topography) should be created.
2. Whether standard values for parameters and variables should be used or whether special values are to be applied.
3. Whether the special initialisation system defined by Nelson and Winter (1982, ch. 13) should be used; here four different parameters may be set low or high by means of binary code ('NW13 = [1,0,1,1]').
4. How to cope with 'random' events. Here we normally apply a (pseudo-) random-number generator, which is central to the behaviour of the model run. If the 'seed' of the sequence of random numbers is not changed, then the result for a given number of firms and periods will always be the same.

As a starting point such questions have been answered in a way which is close to the actions and computations defined by Nelson and Winter (1982, ch. 12). In other words, the present implementation is designed as a compromise between

- (1) closeness to the Nelson and Winter formulations,
- (2) ease of data access and revision of parameters and procedures,
- (3) access to powerful mathematical tools and programming languages.

Thus, the implementation is mainly designed as a simple base for further work rather than as an embodiment of novel viewpoints. To the extent that the system functions and is repeatedly used, it will give novel results through a process of trial and error (see A.1.2). We have, however, to start by simple exercises which demonstrate the basic parameters and the basic behaviour of typical Nelson-and-Winter models. Figure 4.3 gives an example of the initial exercises, namely the development of the productivity levels of 4 firms for 16 periods under a given distribution of innovative and imitative chances (and a given setting of the random-number generator: '\_seed := 2'). Initially all firms have equal market shares, equal research effort and a productivity level of 0.16.<sup>26</sup> However, already in the second period one firm has luck in its innovative R&D and is able to increase its productivity to 0.21. This means that it wants to expand its capital stock. In the fourth period the

situation is changed since another firm makes an innovation. And later both innovations and imitations take place.

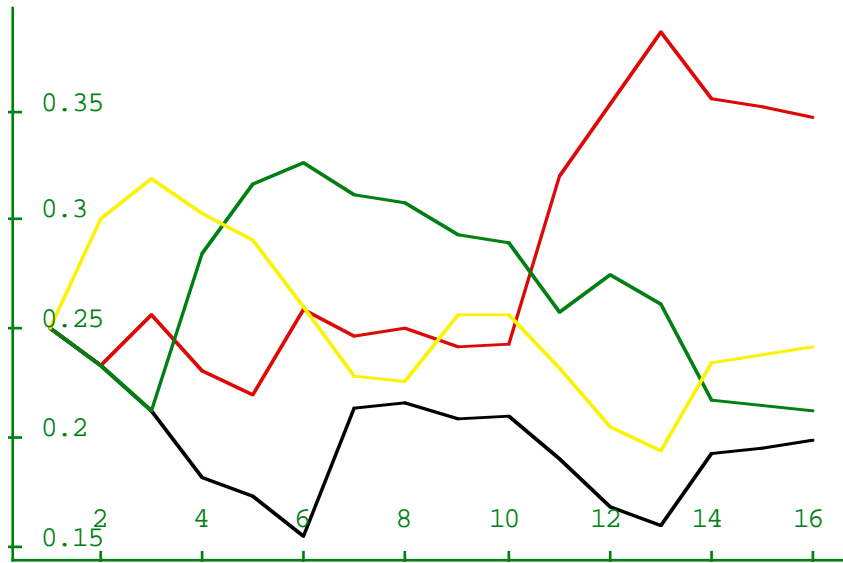


**Figure 4.3.** Productivity levels of 4 firms for 16 periods under a given distribution of innovative and imitative chances ( $\_seed := 2$ ). (Original is in colour to distinguish between firms)

Figure 4.3 demonstrates that the overall productivity level of the industry develops as a result of innovation and imitation. In the latter case a weak firm may suddenly get access to the productivity frontier. Whether this is the case depends on the specification of the possibilities of imitation just as the innovative possibilities are specified by the search space as well as the probability of obtaining an innovative ‘draw’.

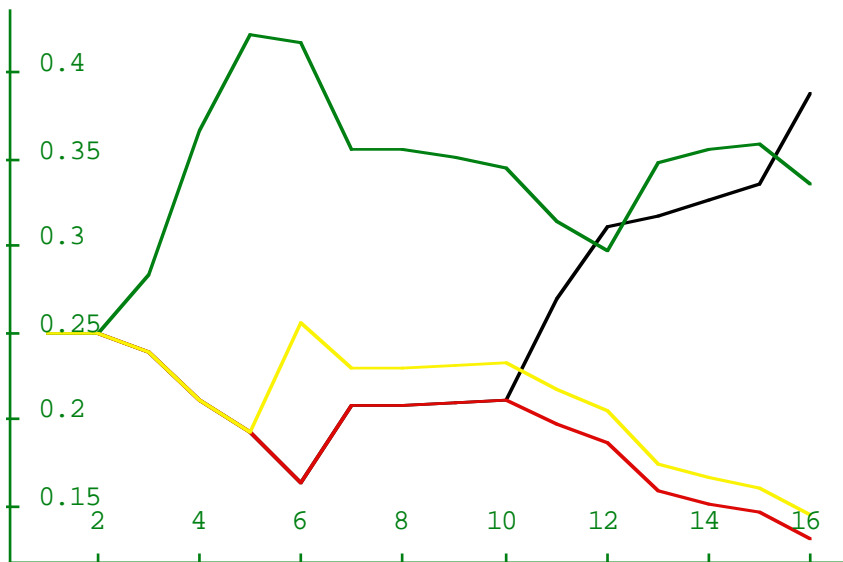
The market shares of firms and the concentration ratio of the industry depend on the relative weight of the two forces. On the one hand a lucky firm may obtain a competitive advantage through innovation. If the other firms are able neither to innovate nor to imitate, then this firm may obtain a monopoly position. This tendency is, however, weakened by the monopolistic practices of dominant firms with little incentive to invest (section A.2.7). On the other hand there is a (decreasing) chance that a weak firm overcomes its weakness through imitation and, to a smaller extent, through innovation.

The development of market shares in a specific run is depicted by figure 4.4. It demonstrates the volatility of the market positions under the chosen conditions. A lucky innovator who alone obtains a high productivity level will increase his capacity and production as a result of the increased productivity as well as of his increased investment activities.



**Figure 4.4.** Market shares of 4 firms for 16 periods under another distribution of innovative and imitative chances (`_seed := 2`). (Original is in colour to distinguish between firms)

Figure 4.4. suggests that no stable pattern is available. But in figure 4.5. another series of random events (based on `_seed := 1`) appears to give another result with an early winner and three unlucky firms among which one escapes the downward trend after period 10.



**Figure 4.5.** Market shares of 4 firms for 16 periods under a certain distribution of innovative and imitative chances (`_seed := 1`). (Original is in colour to distinguish between firms)

This limited experiment serves to demonstrate that the exogenous random-number generator may influence the behaviour of Nelson-and-Winter models heavily while the endogenously generated behavioural patterns may be hidden by this 'noise'. To study the behaviour as the

number of periods is increased radically is of little help since this removes the apparent realism from the exercise. Here we are confronted with a basic problem of most simulation models. This problem has often been solved under strict assumptions but at present we shall not explore it further. The purpose of the present book is to explore models and languages which help us to express both simple and complex evolutionary mechanisms.

#### 4.4. The extendibility of Nelson-and-Winter models

One of the only general rules of model-building is that ‘the proof of the pudding is in the eating’. However, it is not easy to apply the simple Nelson-and-Winter model to most of the mechanisms one would intuitively connect to evolutionary economics. Therefore, the use of the model is largely a question about its extendibility. Before we turn to an evaluation of the model, it is thus important to consider some extensions.<sup>27</sup>

##### 4.4.1. *Satisficing behaviour*<sup>28</sup>

In contrast to other of Nelson and Winter’s models the type presented in sections 4.2.2 and 4.3 does not include satisficing behaviour in an explicit way. This is clearly demonstrated by the fact that the propensities to search ( $r^n$  and  $r^m$ ) are among the constant elements of the model. Thus it is designed to explore the consequences of more rigid modes of behaviour but the reason for its design is probably primarily an attempt to simplify the simulation model and its interpretation. It is, however, not difficult to reintroduce satisficing behaviour, i.e., to operate with decision-makers who consider the major part of reality as consisting of ‘givens’, and only attempt to challenge these ‘givens’ and search for alternatives when their performance become unsatisfactory.

To model this kind of behaviour, we, as a supplement to  $K_{it}$  and  $A_{it}$ , introduce (see Winter, 1984/91, 281 f.) three extra variables in the simple description of the state of the firm (see definitions below): a variable propensity to search innovatively,  $r_{it}^n$ , a variable propensity to search imitatively,  $r_{it}^m$ , and a performance indicator,  $X_{it}$ . The latter (see 4.23) is defined as a distributed lag function of firm  $i$ ’s profit rate, and when it is compared with the industry’s average profit rate, we have a measure of the aspiration level of satisficing behaviour (used in (4.24) and (4.25)).<sup>29</sup> If this level is obtained, no change is made in innovative and imitative search policies. If not, a step towards the industry average is made. Furthermore, the firm decides to commit itself to the new policy for some time in order to allow the policy to ‘work itself out’. This decision is reflected in the increase of  $X_{it}$  with some amount,  $\Delta$ , when a change in search strategy has been made:<sup>30</sup>

$$\mathbf{r}_t^n \equiv (r_{1t}^n, \dots, r_{it}^n, \dots, r_{nt}^n);$$

$$\mathbf{r}_t^m \equiv (r_{1t}^m, \dots, r_{it}^m, \dots, r_{nt}^m);$$

$$\mathbf{X}_t \equiv (X_{1t}, \dots, X_{it}, \dots, X_{nt});$$

$$X_{it} := \phi X_{i,t-1} + (1 - \phi) \pi_{it}; \quad (4.23)$$

$$\left. \begin{array}{l} \text{if } X_{it} \geq \bar{\pi}_t \\ \quad \text{then } r_{i,t+1}^n := r_{it}^n \\ \quad \text{else } r_{i,t+1}^n := \beta r_{it}^n + (1 - \beta) \bar{r}_t^n + u_{it}^n; \\ \quad \quad X_{it} := X_{it} + \Delta; \end{array} \right\} \quad (4.24)$$

$$\left. \begin{array}{l} \text{if } X_{it} \geq \bar{\pi}_t \\ \quad \text{then } r_{i,t+1}^m := r_{it}^m \\ \quad \text{else } r_{i,t+1}^m := \beta r_{it}^m + (1 - \beta) \bar{r}_t^m + u_{it}^m; \\ \quad \quad X_{it} := X_{it} + \Delta; \end{array} \right\} \quad (4.25)$$

where  $X_{it}$  is the perceived performance of firm  $i$ ;  $\phi$  is a parameter which determines the inertia of the performance indicator ( $0 < \phi < 1$ );  $\bar{\pi}_t$  is current industry capital-weighted average profit;  $\bar{r}_t^n$  and  $\bar{r}_t^m$  are the capital-weighted industry average search efforts (policies) of the period;  $\beta$  is a parameter which determines the inertia of the firm's innovative and imitative search policies;  $u_{it}^n$  and  $u_{it}^m$  are random variables<sup>31</sup>;  $\Delta$  is a fixed increment in the perceived performance introduced to stabilise a new search policy.<sup>32</sup>

#### 4.4.2. Exit and entry

There are good reasons to believe that an important part of evolutionary processes are related to the liquidation of some firms and the emergence of others. The economist who has put most emphasis on this aspect of the evolutionary process is the verbal Mark I model of the young Schumpeter while the old Schumpeter emphasises the more routine-like technical change performed by large corporations in his verbal Mark II model.<sup>33</sup> The evolutionary simulations which can be created on the basis of the standard Nelson-and-Winter model ((4.1)–(4.22)) and of its extension with satisficing behaviour ((4.23)–(4.25)) are clearly more related to the Schumpeter Mark II model than to the Schumpeter Mark I model. This bias is immediately discernible from the fact that in these Nelson-and-

Winter models the industry's number of firms,  $n$ , is a constant. There are, however, some possibilities for introducing exit and entry to as well as industry creation and thus to operate with a variable number of firms,  $n_t$ . Such changes will not necessarily change the basic flavour of the Nelson-and-Winter models, but they open the way for a discussion about the differences between Schumpeter Mark I and II. The extension of the Nelson-and-Winter model in this direction is most clearly stated by Winter (1984/91, 283-288) but the elements were also present in earlier versions of Nelson-and-Winter models.

The story of firm exit from the industry is relatively simple. Here we have two cases. First, if a firm invests less than the physical depreciation of the capital stock over several periods, it will in the end fail with respect to a minimum capital stock level,  $K^{\min}$  (which reflects the existence of sharply increasing returns to scale up to this threshold). Second, the perceived performance of the firm,  $X_{it}$  (see (4.23)), may fall below a critical negative level,  $X^{\min}$ . This means that the firm relatively persistently is showing an unacceptable performance. In both cases the firm is liquidated and its capital is scrapped:

$$\left. \begin{array}{l} \text{if } (K_{i,t+1} < K^{\min} \text{ or } X_{i,t} < X^{\min}) \\ \text{then } K_{i,t+1} := 0; \end{array} \right\}^{34} \quad (4.26)$$

Firm entry to the industry raises some more complicated problems which relate to the profit-seeking activities of actors which are not producing the product of the industry we are modelling. In a highly stylised manner, we may articulate these activities in terms of costly innovative and imitative search like the activities we find within the industry ((4.7) and (4.8)<sup>35</sup>). Taken as an aggregate, external actors are involved in search activities (R&D) which will occasionally give results with respect to the production technique of the industry under study. This leads to some number ( $N \geq 0$ ) of external actors who in each period have success in achieving relevant information about the techniques of the industry. We may assume that this number have a Poisson probability distribution with a parameter proportional to the cost of industry-external search.

Whether a 'draw' by an external actor leads to entry to the industry depends on whether the successful searcher thinks that the obtainable productivity allows a profit rate which exceeds some critical level  $\pi^{\min}$  (the 'entry barrier' level). The relevant information is not fully available and therefore a random error in the firm's evaluation of the production conditions of the industry is introduced. If a firm decides to enter, then it applies the technique it has found and establishes an initial capital stock, initial search policies and an initial level of performance. When we take into account the difference between innovative and imitative search of the external actors, we obtain the following statements:<sup>36</sup>

$$\mathbf{A}_t(t) \equiv (A_{1t}, \dots, A_{it}, \dots, A_{n(t),t});$$

$$\mathbf{K}_t(t) \equiv (K_{1t}, \dots, K_{it}, \dots, K_{n(t),t});$$

$$\mathbf{r}_t^n(t) \equiv (r_{1t}^n, \dots, r_{it}^n, \dots, r_{n(t),t}^n);$$

$$\mathbf{r}_t^m(t) \equiv (r_{1t}^m, \dots, r_{it}^m, \dots, r_{n(t),t}^m);$$

$$\mathbf{X}_t(t) \equiv (X_{1t}, \dots, X_{it}, \dots, X_{n(t),t});$$

$$\gamma_{it}^{\text{ne}} := d^{\text{ne}} \cdot R^{\text{ne}}; \tag{4.27}$$

$$N_t^{\text{ne}} := \theta^{\text{ne}}(\gamma_{it}^{\text{ne}}); \tag{4.28}$$

repeat  $N_t^{\text{ne}}$  times

$$A_e := \psi^e(A^{\text{init}}, \varphi, t);$$

if  $(P_t A_e - c > \pi^{\text{emin}} + u_{et})$  then

$$A_{n+1,t+1} := A_e;$$

$$K_{n+1,t+1} := \xi(K^e, \sigma^k, K^{\text{min}});$$

$$r_{n+1,t+1}^n := \bar{r}_t^n + u_{it}^n;$$

$$r_{n+1,t+1}^m := \bar{r}_t^m + u_{it}^m;$$

$$X_{n+1,t} := \Delta;$$

$$n_t^{\text{id}} := n_t^{\text{id}} + 1;$$

$$\left. \begin{array}{l} \text{repeat } N_t^{\text{ne}} \text{ times} \\ A_e := \psi^e(A^{\text{init}}, \varphi, t); \\ \text{if } (P_t A_e - c > \pi^{\text{emin}} + u_{et}) \text{ then} \\ A_{n+1,t+1} := A_e; \\ K_{n+1,t+1} := \xi(K^e, \sigma^k, K^{\text{min}}); \\ r_{n+1,t+1}^n := \bar{r}_t^n + u_{it}^n; \\ r_{n+1,t+1}^m := \bar{r}_t^m + u_{it}^m; \\ X_{n+1,t} := \Delta; \\ n_t^{\text{id}} := n_t^{\text{id}} + 1; \end{array} \right\} \tag{4.29}$$

$$\gamma_{it}^{\text{me}} := d^{\text{me}} \cdot R^{\text{me}}; \tag{4.30}$$

$$N_t^{\text{me}} := \theta^{\text{me}}(\gamma_{it}^{\text{me}}); \tag{4.31}$$

$$\left. \begin{array}{l}
\text{repeat } N_t^{\text{me}} \text{ times} \\
A_e := \max[A_{1t}, \dots, A_{it}, \dots, A_{nt}]; \\
\text{if } (P_t A_e - c > \pi^{\text{emin}} + u_{et}) \text{ then} \\
A_{n+1,t+1} := A_e; \\
K_{n+1,t+1} := \xi(K^e, \sigma^k, K^{\text{min}}); \\
r_{n+1,t+1}^n := \bar{r}_t^n + u_{it}^n; \\
r_{n+1,t+1}^m := \bar{r}_t^m + u_{it}^m; \\
X_{n+1,t} := \Delta; \\
n_t^{\text{id}} := n_t^{\text{id}} + 1;
\end{array} \right\}^{37} \quad (4.32)$$

where the following new notation is introduced:  $\mathbf{K}_t(t), \mathbf{A}_t(t), \mathbf{r}_t(t), \mathbf{r}_t(t), \mathbf{X}_t(t)$  are the arrays describing the state variables but their number of elements ( $n(t)$ ) have now become time-dependent; each time a new firm is created the number of elements in all the arrays are increased by one;  $N_t^{\text{ne}}$  and  $N_t^{\text{me}}$  are the numbers (each  $\geq 0$ ) of potential entrants at the end of period  $t$  due to industry-external innovative and imitative search;  $\theta^{\text{ne}}(\cdot)$  and  $\theta^{\text{me}}(\cdot)$  are the functions which determine the number of entrants for a period and ensure that this number has a Poisson probability distribution; the means of the distributions are  $\gamma_{it}^{\text{ne}}$  and  $\gamma_{it}^{\text{me}}$ ; they are determined by the (for simplicity unchanging) levels of industry-external search expenditure which may lead to information about applicable production techniques,  $R^{\text{ne}}$  and  $R^{\text{me}}$ , as well as be the efficiency coefficients of these efforts,  $d^{\text{ne}}$  and  $d^{\text{me}}$ , i.e., the probabilities that a unit of innovative and imitative search expenditure will lead to success;  $A_e$  is a local variable denoting the capital productivity which is obtainable through the technique found by a potential entrant,  $e$ ;  $\psi^e(\cdot)$  is the probabilistic function determining the outcome of an innovative ‘draw’ by an external actor (see (4.11));  $\pi^{\text{emin}}$  is the minimum level of profit per unit of capital required by the potential entrants (and their banks);  $u_{et}$  is a random variable<sup>38</sup> which represents an error term in the information and calculation of a potential entrant;  $A_{n+1,t+1}, K_{n+1,t+1}, r_{n+1,t+1}^n, r_{n+1,t+1}^m, X_{n+1,t}$  are newly created state variables for the new firm of the industry;  $\xi(\cdot)$  is the function which probabilistically determines the initial capital stock of the entrant with a mean value  $K^e$ , a standard deviation  $\sigma^k$ , and a downward truncation determined by  $K^{\text{min}}$ ;  $n_t^{\text{id}}$  is a variable which is used for the naming (by an identification number) of new firms of the industry.

#### 4.4.3. Industry creation

When the problems of entry have been dealt with, there is no large step to start a simplified study of industry creation. Basically, the simulation model ((4.1)–(4.32)) can be used although we have to introduce minor modifications. The study of industry creation is thus basically a case of running the model after a little reprogramming and the definition of special parameter values. In the present context it is, however, more helpful to demonstrate how the above exposition of entry to the industry illustrates a procedure which may be extended to a treatment of industry creation.

In principle we just start with  $n_t^{\text{id}} = 0$  and then we let the search activities of the external actors find the industry and start it up on the basis of (4.27) to (4.29).<sup>39</sup> In the beginning one or more founders or *Gründer* are successful in the background innovative search. In other words, he finds a production technique allowing him to produce the product. To decide whether to invest and start producing the product he needs some initial information about the price of the product as well as of production inputs. A justification of the application of the entry model may be found in the fact that the demand-price of a new product is often judged on the basis of an existing product which is functionally more or less equivalent to it. Input prices may also be assumed to be known. Thus, the founding of an industry is dependent upon 1) the level of background search, 2) the demand-price for the first products delivered, 3) the production technique found and thus the initial profitability. Further factors are: 4) the minimum scale of investment and production and 5) the financial conditions of potential entrants, including bankers' rules about finance of industry creation (and thus their way of coping with asymmetric information between lender and borrower in the case of founders).

We now turn to the evolution of the newly created industry.<sup>40</sup> In the industry there is initially a large profit rate (at least enough to overcome the entry barrier, see the condition in (4.29)). The rate of expansion of the firms of the industry as well as the rate of entry to the industry is high (relative to later). The initial search efforts of the firms of the industry are low according to the rules of satisficing behaviour ((4.24)–(4.25)). Consequently, the level of capital productivity is low. However, the expansion of the output of the industry will diminish profits and this will lead to negative evaluations of the performance of the firms. This in turn will lead to an increase in innovative and imitative search efforts (in steps because of the heuristic rule allowing some time for new search strategies to work themselves out). In any case, we see an increase in productivity which eases the pressure on profit.

With respect to the number of firms of the industry,  $n_t$ , we see an initial increase. However, since there is no feedback from the profitability of the industry to the search efforts of the external actors in

the present version of the model, the growth in the number of firms may be relatively slow. In any case, by entry and internal expansion the industry will sooner or later reach a capacity level and a demand-price which means liquidation for some firms (4.26). Here the casualties are firms with below-average productivity. The survivors are winners in the sense that exit leads to a scrapping of part of the productive capacity of the industry and thus to an increase in profits.<sup>41</sup>

#### *4.4.4. Product quality, product innovation and imitation*

A central weakness of the Nelson-and-Winter models is that they deal solely with production techniques and thus delimit their focus to process innovation and imitation. In the actual evolutionary-economic processes, product innovation and imitation appears to be much more important, especially for the activities we call R&D. However, the Nelson-and-Winter scheme is flexible enough to allow a crude treatment even of these issues. One possibility, developed by Gerybadze (1982, chs. 3-5), is to expand the application of the scheme to the interaction of firms which sells and buy a certain type of product. Another possibility is to emphasise that while

Winter argues persuasively for adaptive modeling of firm behaviour ... [t]he case for adaptive consumer modeling is stronger, since consumers are less able to bear the cost of computing optima and since inefficient consumers will not be driven out of existence. (Smallwood and Conlisk, 1979)

Even if the latter possibility represents a major break with the Nelson-and-Winter family of models, it is enlightening to make a short excursion into the area of stochastic quality attributes.

#### *An excursion on consumers and product quality*

To start with, brand quality can be considered as the probability that a single specimen of the brand received by the buyer will not reveal itself as being of an unsatisfactory quality during the normal period of use. High quality means a low probability for a unit of the brand to show a 'breakdown', an inadequate performance seen from the viewpoint of the buyer (Smallwood and Conlisk, 1979, 3). The task of the buyer is to learn about the breakdown probability for each brand and choose accordingly.

In the model, buyers tend to follow simple adaptive strategies with respect to such goods. In this way they try to cope with the fact that (1) they are poorly informed in comparison to sellers, (2) any attempt to overcome the asymmetric information would run into their competence-difficulty gap (Heiner, 1988) which is especially marked with respect to issues which involve stochastic product quality, (3) a relatively consistent following of simple heuristic rules may accumulate knowledge of the credence qualities of brands—either in the individual or the buyers as a group.

The most obvious strategy is that of satisficing. which we have until now seen from the viewpoint of firms, but it seems even more obvious in the modelling of the behaviour of non-specialist buyers. For them satisficing behaviour is based on two basic rules which are applied by each buyer.

Rule I: if the brand chosen by the buyer in the last purchase has not shown unsatisfactory behaviour to him, then the same brand is chosen in the present purchase.

Rule II: if the brand chosen by the buyer in the last purchase has shown unsatisfactory behaviour, then a search is performed in order to find a better brand to be chosen in the present purchase.

To the extent that rule II is specified in a way which takes into account other buyers' experiences with the different brands, then a collective learning process about brand quality may take place. The learning among buyers may, however, not be sufficient if a 'breakdown' is a rare but very grave event. In this case we may have to introduce another rule of social learning:

Rule III: if the brand chosen by one of the other buyers in the last purchase has shown unsatisfactory behaviour and if this becomes known to the buyer, then a search is performed in order to find a better brand to be chosen in the present purchase.

To the extent that this rule is not sufficient we come to

Rule IV: if a basic doubt exists about a grave form of breakdown and if this doubt cannot be removed by the seller, then a third party (e.g. the government) is introduced in order to ensure that all units of all brands have a minimum level of quality.

The rules of satisficing behaviour presuppose to a larger or smaller degree that the credence qualities emphasised by different buyers are (to some extent) the same. Rules III-IV raise still stronger demands on buyers' ability to define and communicate about credence qualities. Furthermore, we see that the rules presuppose a certain structure with respect to supply-side organisation. Underlying rules I-III is the assumption that the brands of the different sellers show a well-defined and stable (or only slowly changing) probability of unsatisfactory performance.

The behaviour of a simplified system based on rules I-II can be described in terms of a Markov process. The core idea is that buyers' experiences with the units of the brands in their possession during a particular period of time determine the market shares of the different brands in the next period. This idea has been explored by Smallwood and Conlisk (1979).

Their standard model is based on the assumption that all brands are almost identical. They are identical with respect to price and any directly observable quality. But they differ with respect to credence quality. Each product lasts one period but during this period the probability of breakdown is dependent on the brand that the unit belongs to. Each of the  $n$  brands is characterised by a positive probability of breakdown. The probability that brand  $i$  used during period  $t$  will breakdown is  $b_{it}$ . For instance, this probability may be 0.2, meaning that from a large sample of units of brand  $i$  80% will be satisfactory while 20% will show some sort of breakdown.  $\mathbf{b}_t$  is the vector of breakdown probabilities and they may differ across brands. For simplicity, we shall normally assume that breakdown probabilities are non-changing through time.<sup>42</sup>

Each buyer buys one product in the beginning of each period,  $t + 1$ . He cannot discern its quality by pre-purchase inspection but only by post-purchase experience of a breakdown. If no breakdown is experienced with the brand in his possession during period  $t$ , then he buys a unit of the same brand in the beginning of period  $t + 1$ . If a breakdown is experienced with the brand in his possession during period  $t$ , then he performs a search for a better brand before he decides which brand to buy in the beginning of period  $t + 1$ .

In the model the outcome of the search for a better-quality brand is stochastically dependent of the market shares of the different brands during period  $t$ . The market share of brand  $i$  in period  $t$ ,  $m_{it}$ , is simply the fraction of buyers who have bought this brand at the beginning of the period. The situation for all brands is summarised by the market share vector,  $\mathbf{m}_t$ . Assuming a decision-making process which to some extent reflects quality of brands, the market shares can be taken as a more or less precise indicator of credence qualities. If market shares are good indicators, the buyer would like to choose the brand with the highest market share. But in some cases there might be no correlation between market share and quality. In other cases the buyer would not know market shares but only the way they are reflected in the probabilities that he will meet other buyers who know the different brands or sellers who sell the different brands.

The dissatisfied buyer can have different degrees of confidence in the ability of the market selection process to detect high-quality brands and different abilities to recognise the market shares of different brands. The empirical result will be a stronger or weaker relationship between market shares and the choice of the dissatisfied buyer. Smallwood and Conlisk (1979, 5 ff.) rely heavily on this parameter,  $\alpha$ , the sensitivity of brand choice to market shares. The dissatisfied buyer chooses the brand for the next period with probabilities that are proportional to the market shares. For instance, the probability that a dissatisfied buyer chooses brand  $j$  in period  $t + 1$  is proportional to  $m_{jt}^\alpha / \sum_{k=1}^n m_{kt}^\alpha$ , for  $\alpha \geq 0$ . If  $\alpha = 0$ , the

buyer has no confidence in market shares as an indicator of quality; instead he chooses a brand at random. If  $\alpha = 1$ , the buyer has an intermediate confidence in market shares as an indicator of quality; he chooses a brand with a probability which is equal to its market share. If  $\alpha = \infty$ , the buyer has maximum confidence in market shares as an indicator of quality; he simply chooses the brand with the highest market share.

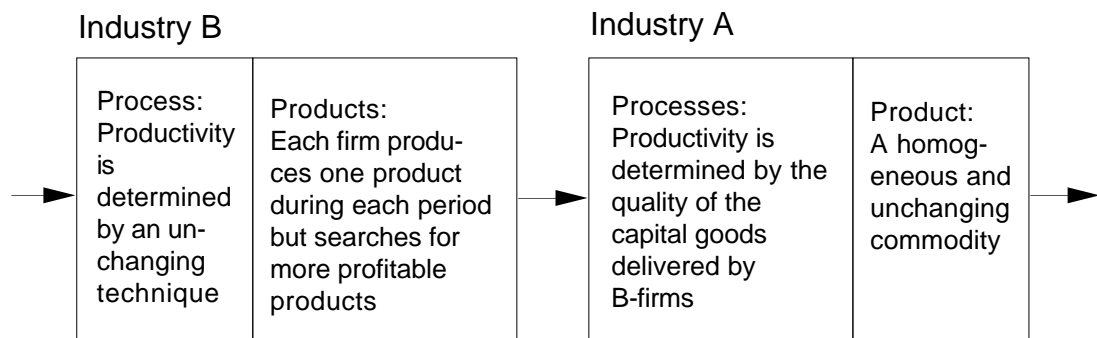
We have now defined a Markov process which is only reflecting choices of the buyers. Such a Markov process will more or less rapidly converge towards a state of equilibrium where the market share of each brand has reached an equilibrium level where for brand  $i$  we have that  $m_{i,t+1} = m_{it}$ . The question is now how these equilibrium market shares reflect the credence qualities of the different brands of piglets. At the one extreme we may find that only brands of the highest quality have a non-zero market share. At the other extreme we may find that the market selection process has not been able to discern the high-quality brands from the low-quality brands. It is hardly surprising that the answer (which is given by the simple mathematics of Markov processes) is heavily dependent on the buyers' confidence in the quality signals of the market,  $\alpha$ . The correspondence between quality and market shares peaks for  $\alpha = 1$  and falls for higher and lower parameter values. Too much confidence in the market signals gives a large probability that brands which for random reasons started with a relatively high market share dominate the equilibrium state. Too little confidence in the market allows brands of different quality levels to coexist but with smaller market shares of weak-quality brands than in the initial situation.

The problematic character of the equilibrium state becomes even more obvious if we introduce more radical buyer reactions to quality breakdowns. We may, e.g., take into account that a buyer who has discovered a breakdown of a particular brand will not include this brand in his search for the next choice. This behaviour decreases the application of the best-performing brand which also shows breakdowns. The 'correct' behaviour would be not to overreact when facing a breakdown of a unit of a brand and give the same brand a chance in the next choice. The overreaction to breakdown can also occur if we allow longer memories about unsatisfactory performance and stronger communication between buyers.

### *Possible models of product innovation and imitation*

We now return to the main line of argument: how can Nelson-and-Winter-like models be adapted to cope with product innovation and imitation. Here we are entering a zone which confronts us with a whole series of new questions and complexities which have not yet been solved. In the present context we have only the possibility of glancing at a few possibilities (some of which have not yet been explored in the literature).

We start by rethinking the change of production techniques which has hitherto been considered as the introduction of disembodied techniques, i.e., techniques which can be introduced without respect to the quality of the capital equipment. Now we introduce embodied technical change where the increased productivity can only be obtained by introducing capital equipment of a higher quality. We discuss embodied technical change in a two-industry framework (see figure 4.2) which provides one of the simplest ways of introducing product-variety and variety-creation in the Nelson-and-Winter scheme. Here we may think of the type of capital-using industry we have been studying in most of the present chapter as industry A. The industry which produces the capital equipment for industry A is called industry B. The possibilities to continue to increase productivity in industry A depend on the ability of the firms in industry B to continue to find product innovations and to expand production of them by accumulation in the innovating B-firm and imitation from other B-firms.



**Figure 4.2.** The set-up for product innovation and imitation in a capital equipment industry (industry B).

We start looking at this set-up from the viewpoint of the A-firms. In the previous models the capital equipment had no influence whatsoever on productivity because we assumed a disembodied form of technical change. Any new production technique could immediately be applied irrespective of the use of quite old vintages of capital. Now the A-firms can only introduce new techniques and thus higher levels of productivity in companionship with new capital equipment. Furthermore, we assume that this equipment is not produced by industry A but only by industry B. This removes the whole rationale for innovative and imitative search in industry A.<sup>43</sup> Instead the problem of the A-firms is to find the capital equipment with the best performance relative to its price.

Let us now approach the problem from the side of the B-firms. They have the possibility of producing a large but also largely unknown set of capital goods. To simplify, we assume that each B-firm uses its full production capacity to produce one type of capital good. Its production capacity is not dedicated to this type of good, and it may change to produce another good at the end of each period. All goods are produced

with the same physical productivity. The only thing which makes them different is the way they function in industry A. The potential capital goods are assumed to be clearly distinct with respect to the productivity they ensure for the A-firms who are able to order them with respect to physical productivity per capital unit.

Given these assumptions, we may rethink the story told by statements (4.1)–(4.22). First of all, we need a description of the new situation:

1. We need to specify the set of B-firms. Furthermore, we must specify the set of possible products (capital goods) of industry B. We may, e.g., imagine that the search of the B-firms during a large range of periods may at the very best discover 100 different potential products each of which is provided with an identity number (see general definitions below).
2. To simplify further we assume that each existing B-firm will produce one and only one product during a period,  $t$ , and that the products produced in period  $t + 1$  are decided by the B-firms during period  $t$ . This gives us a new element in our state description of industry B, namely a mapping between B-firms and products implemented as an array (see below).
3. Finally, we give characteristics to the potential products. For simplicity we assume that they are all identical with respect to their unit cost of production for the B-firms. However, the A-firms are able to discern between their quality because they lead to different output/capital ratios when applied in industry A. Let us distribute capital productivities to the 100 potential products, e.g., productivities distributed randomly between a very low and a very high level.

With these definitions we may formulate the process by which the capital goods produced and applied change over time.

1. To simplify we assume that the demand-prices of the A-firms for different capital goods strictly reflect their quality differences (4.33–4.34). This means that we assume full substitutability between the capital goods and full information on the part of the A-firms.<sup>44</sup>
2. Through their costs of innovative and imitative search (see (4.6)–(4.7), (4.9)–(4.10). (4.12)–(4.13)), the B-firms may succeed in having a 'draw' in the innovative and imitative 'lottery'. The probability of success depends on technological and institutional conditions which have to be specified in terms of their influence on the probability distributions.
3. The result of an innovative 'draw' (4.35) must be specified. We may, e.g., assume that the successful development of a new product is conditioned by the availability in the B-firm of 'tacit knowledge' which is related to earlier products produced by the firm. For this

reason, a firm is most likely to find products with a quality closely related to its earlier experience.

4. The result of an imitative ‘draw’ may be formulated in analogy to (4.14).
5. These specifications create a clear-cut decision-problem for the B-firms at the end of each period: to proceed with the good it is producing or to shift to another good. The possibility to make a change is the probabilistic outcome of search processes of the B-firms. They choose the possibility which has the highest quality in the eyes of the A-firms (4.37).

Through these modifications of the Nelson-and-Winter models we have core elements of an evolutionary model with product innovation and imitation. However, the missing elements are not simple to provide without greatly increasing the level of complexity (e.g., in terms of different vintages of capital in A-firms, scrapping rules of A-firms, etc.). Here we should just remark that some simple kinds of product innovation and imitation may be within the reach of a Nelson-and-Winter-type model. Some of the formal elements such a model should include are summarised in the following statements which mainly concern the firms in industry B:

$$f_B^{\text{id}} \equiv \{1, \dots, i, \dots, n\};$$

$$g^{\text{id}} \equiv \{1, \dots, j, \dots, m\};$$

$$G_{Bit}' \equiv (i, g_t) \text{ where } i \in f^{\text{id}}, g_t \in g^{\text{id}}; \text{ or, simpler: } G_{Bit} \equiv g_t;$$

$$G_{Bt} \equiv (G_{B1t}, \dots, G_{Bjt}, \dots, G_{Bnt});$$

$$A_A \equiv (A_{A1}, \dots, A_{Aj}, \dots, A_{Am}) \text{ where } j \in g^{\text{id}};$$

$$\text{constraint: } \underline{\text{if}} A_{Aj} > A_{Al} \underline{\text{then}} P_{jt} > P_{lt}; \quad (4.33)$$

$$P_{jt} := D_A(A_{Aj}, Q_{jt}); \quad (4.34)$$

$$\left. \begin{array}{l} \underline{\text{if}} \theta_{Bit}^n = \text{true} \\ \underline{\text{then}} G_{Bit}^n := \psi^g(\dots) \\ \underline{\text{else}} G_{Bit}^n := G_{Bit}; \end{array} \right\}^{45} \quad (4.35)$$

$$\left. \begin{array}{l} \text{if } \theta_{Bit}^m = \text{true} \\ \text{then } G_{Bit}^m := \max[A_A(G_{Blt}), \dots, A_A(G_{Bit}), \dots, A_A(G_{Bnt})] \\ \text{else } G_{Bit}^m := G_{Bit}; \end{array} \right\}^{46} (4.36)$$

$$G_{Bi,t+1} := \max[A_A(G_{Bit}), A_A(G_{Bit}^n), A_A(G_{Bit}^m)]; \quad (4.37)$$

where  $f_B^{\text{id}}$  is a set of identifiers of B-firms;<sup>47</sup>  $g^{\text{id}}$  is a set of identifiers for potential capital goods/products;  $m$  is the number of potential products in all periods;  $G_{Bit}$  is the identification number of the capital good produced by firm  $i$  during period  $t$ ;  $G_{Bt}$  is the array describing the state of the firms of industry B with respect to their product choices in period  $t$ ;  $A_A$  is an array which to each potential capital good ascribes a capital productivity, seen from the users' (the A-firms) point of view;  $A_{Aj}$  is the productivity of the  $j$ 'th capital good;  $j$  and  $l$  are two arbitrary goods;  $P_{jt}$  is the price of the  $j$ 'th good;  $D_A(\ )$  is the demand-price function for the inputs to industry A;  $\theta_{Bit}^n$  and  $\theta_{Bit}^m$  are described in (4.10) and (4.13);  $G_{Bit}^n$  and  $G_{Bit}^m$  are the products found by successful innovative and imitative search of a B-firm;  $\psi^g(\dots)$  is the function which probabilistically determines the outcome of an innovative 'draw' of a B-firm.

The relevance of this formal apparatus is dependent on the large set of problems which can be explored with its help. However, such an exploration presupposes further developments of the Nelson-and-Winter framework which are beyond the limits of the present book. However, some applications in relation to non-linearities of the search space at the borders of national systems of innovation will be dealt with below.

#### 4.5. Appreciating Nelson and Winter's modelling scheme

The foregoing presentation of a typical Nelson-and-Winter model as well as some extensions has been rather intricate but it has, hopefully, served its purpose: to demonstrate that Nelson and Winter have developed a computer-implementable concept of an evolutionary-economic process. This concept owes much to Simon and other contributors to Behavioural Economics but also includes several other ideas as well as a lot of synthetic work. Through the study of the extendibility of a typical Nelson-and-Winter model (section 4.4), it has also been demonstrated that it is not the specific assumptions underlying their standard model (sections 4.2.2 and 4.3) which should be used as the standard criteria to evaluate their research programme. The typical models as well as the concrete simulation experiments are (as claimed by Nelson and Winter)

examples rather than primary results to be evaluated. Instead, we should try to evaluate Nelson and Winter's promotion and exploration of an extremely broad class of models which provides us with a language as well as analytical tools for studying evolutionary processes. A major test is whether Nelson and Winter's evolutionary scheme helps us express such processes as well as reconstruct contributions to the old evolutionary economics.

Nelson and Winter have not been particularly successful in persuading their readers to focus on these kinds of issues, if we may judge from the literature on technical change, theory of the firm, etc. Instead of discussing the Nelson-and-Winter evolutionary research programme as a whole, many readers have chosen to select small parts for citation. In this way Nelson and Winter have been widely cited but their work has only to a small extent been further developed. Nelson and Winter already appear likely to become 'footnote economists', just like Schumpeter. But their work is not very well-suited for this role.

By reflecting upon the character of the task confronted by Nelson and Winter, we may make an *a priori* characterisation of some of the criticism of their results.<sup>48</sup> Non-evolutionary economists may think that evolutionary simulations are unclear ways of reaching results which can be demonstrated with much more clarity and elegance if substantial rationality is not excluded from the analysis. Methodologists may conclude that we have yet another example of the unclear scientific status of evolutionary theory and simulation. Researchers whose individual contributions are included in the synthetic evolutionary process may remark that many of their insights are excluded and that they can easily provide counterexamples against the specific mechanisms which are applied. Representatives of the traditions of the old evolutionary economics may emphasise the primitive character of the model of the evolutionary process which does not include many of their favourite ideas. Statisticians and historians may point out that the quantitative outcome of the simulations relies on arbitrary assumptions and that almost any complex model can be 'calibrated' to fit real data series. Policy-makers may express their disappointment at the lack of clear-cut policy implications.

We could extend this distressing list of types of criticism, but it has little purpose. The real success criterion is whether the creation of a family of synthetic evolutionary-economic processes helps the establishment of a progressive evolutionary-economic research programme (Lakatos, 1970). In other words, we may ask whether Nelson and Winter have helped to create a research programme which increases the understanding of economic evolution and the ability to answer the various criticisms. To me it is clear that in a very general way the answer is 'yes', even if the concrete specifications of Nelson and Winter's models are already beginning to look old-fashioned a decade after the publication of their famous book. The Nelson-and-Winter models have helped others

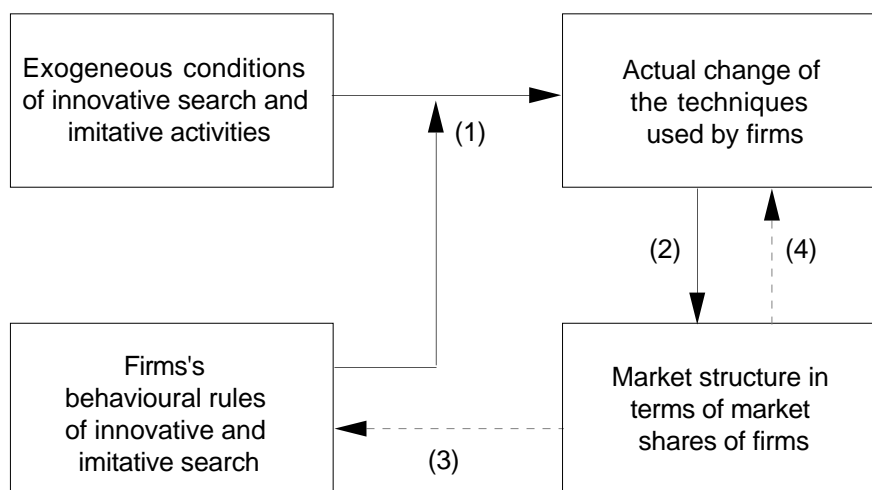
by demonstrating that it is not impossible to treat evolutionary-economic processes in a systematic way. However, it is also clear today that they have not themselves provided a specification of an evolutionary-economic research programme. For example, they have not helped to develop an evolutionary approach to economic transactions (see ch. 4). Furthermore, they have not answered the sceptical comment that their results are simply the outcome of the stochastic character of their models (which is so central to the description of the structure of the search spaces, etc.). Therefore, it is difficult to say whether this element is dispensable or at the very core of evolutionary thinking.

The present emphasis on the basic issues of Nelson and Winter's scheme should not be seen as an attempt to belittle the many examples of applications of simulation exercises that they have provided. It would be nice to have room for discussing the applicability of the Nelson-and-Winter family of models in analyses of economic selection in the manner of Alchian (Nelson and Winter, 1982, ch. 6); factor substitution (ch. 7); economic growth (ch. 9); backwardness and catching-up (ch. 10); general industrial dynamics (chs. 12-14); the role of finance in technical change (ch. 12 and the work of Schuette, 1980); creation of, entry to and exit from an industry (Winter, 1984/91); product change and industrial structure (Gerybadze, 1982). These examples give plenty of material for studying the ways in which the Nelson-and-Winter scheme helps but also sharply focuses (not to say: distorts) the study of evolutionary processes. These examples also allow us to consider how we may adjust their basic scheme and toolbox in order to make them better match the diverse purposes to which they may be applied.

Let us finish this chapter with such an example: market structure or industrial concentration in terms of market shares of the different firms of an industry. Here we see an important difference between evolutionary and structuralist approaches. The structuralists tend to treat the relative market shares as structures, i.e., relatively stable phenomena which help to explain more flexible phenomena (e.g., the conduct of firms and the resulting technological and economic performance). The evolutionists often treat the market 'structures' as relatively flexible patterns to be explained by other factors. Thus, the two approaches often miss each other's points, since what is considered to be the *explanandum* by the one party is the *explanans* of the other party, and *vice versa*.

In this context Nelson and Winter are clearly evolutionists. But what about Schumpeter? Actually, the old Schumpeter appears in his Model II to join a simple structuralist paradigm by developing an argument about the role of 'big business' (Schumpeter, 1942/87, ch. 8). This argument has later been presented as the 'Schumpeter hypothesis' of the superior innovative abilities of large corporations. However, in its crude form this hypothesis should be ascribed to Galbraith who emphasises the importance of firm size *per se* (Galbraith, 1952/72, ch. 7): 'Because development is costly, it follows that it can be carried on only by a firm

that has the resources which are associated with considerable size.<sup>49</sup> But for an evolutionary perspective, the argument seems to be wrongly put: the market structure is just as much a result as a cause of technological development. This point was developed by Nelson and Winter (1982, chs. 13-14) in a series of simulation experiments, but here we will concentrate on the structure of the argument which may help us to rethink the ‘Schumpeter hypothesis’. The following short discussion will refer to figure 4.3.



**Figure 4.3.** Simplified relations between technical change and market structure in Nelson and Winter's and related models.

In the Nelson-and-Winter models discussed above, the chain of causation runs from the exogenous conditions of search as well as the relevant behavioural rules of firms to the technical change of the industry under consideration (arrow 1 of figure 4.3). Given the productivity of firms (and their capital stock), we immediately have the market shares of the individual firms (arrow 2). Here much of Nelson and Winter's work stops. It is, however, possible to create feedback from market structure via rule change (arrow 3) to productivity performance. One story may be that firms with very large market shares have a sharp decrease in motivation for expanding their capacity. For this reason, they may reduce their search costs. The opposite story is that firms with very large market shares want to expand capacity and search costs to create a barrier to entry for outside firms.

In this setting we see that Galbraith was only emphasising the feedback loop (arrow 3). His argument may be rephrased in terms of a minimum level of innovative search costs (economies of scale and scope in R&D). Schumpeter's argument was much broader and includes the elements covered by Nelson and Winter. However, his phrase about 'the perennial gale of creative destruction' (Schumpeter, 1942/87, 87) emphasises that the firms' change of techniques should not always be seen as a gradual process. In this perspective the pace of technical change is increased by

competition in a more dramatic way than has been discussed up to now. First, we note that Schumpeter thinks in terms of two modes of technical change and two corresponding types of behavioural rules. In the 'entrepreneurial mode', the search work is performed before entry to the industry (see sections 4.4.2-4.4.3). In the 'routinised-search mode', large corporations succeed in incorporating search into their normal business activities. In this perspective, the growth of firms reaches a threshold which allows a basic change in behavioural rules (arrow 3). Second, we may consider the immediate effect of the large firms (with high productivity) upon the rest of the firms. The latter are simply squeezed out of the industry, and it is not only their capital but also their techniques which are scrapped. Therefore, we see a direct link from market structure to technical change (arrow 4).

This short discussion of the relationship between technical change and market structure has helped to emphasise that we should normally use Nelson and Winter's scheme rather than a concrete example of their models. The same need is demonstrated if we consider Nelson and Winter's treatment of the nature of the search processes underlying the change of rules. With respect to the individual firm it is a question of the amount of resources applied for innovative search for new rules and imitative search with the purpose of copying the rules of more competitive firms. But the incentives to perform search and the probability of being successful depend on the structure, or the 'topography', of the search space. The latter term is used 'to suggest the role of the cognitive conditions under which the search for new methods takes place. The topography of innovation determines what possibilities can be seen from what vantage points, how hard it is to get from one spot in the space of possibilities to another, and so forth.' (Nelson and Winter, 1982, 229)

The explicit consideration of the topography of the search space is an important way of approaching national systems of innovation (Lundvall, 1992). But first we have to connect the search space to economic and political facts. In other words, we want to consider the importance of the nation in terms of the degree of deformation or discontinuity of the search space at the national border. To do so is not easy in the context of Nelson and Winter's concrete modelling exercises since they only deal with search for production techniques in a search space which has little economic structure. This makes it difficult to introduce the idea of national systems of innovation and it even represents a radical delimitation of the concept of 'locality' in the argument of Nelson and Winter, which is especially clear if the search and selection spaces are taken together. To use a metaphor: there are no 'Galapagos Islands' in their topography and thus no chance of developing and testing new variants under specialised conditions before they are tested in the more hostile environment at the mainland or the world market.

The most obvious extension of Nelson and Winter's treatment of the search space is provided by their treatment of imitative search. Even in this case all firms are equally near or far from each other. However, we may distinguish between the probability of imitating firms within the same nation and foreign firms (omitting multinational enterprises). In this way we come to appreciate the coevolutionary path of the firms of a given nationally located industry. If one firm is successful in innovation or in imitating foreign firms, this has a spill-over effect on the other nationally located firms because of the topography of the search space. This idea is relatively easy to implement in terms of evolutionary simulation models.

More complex problems are raised when we turn to the economic and political aspects of the space of innovative search. However, we have a possibility to do so if we combine Nelson and Winter with the idea of interactive innovation (Andersen and Lundvall, 1988; Lundvall, 1992). In relation to the model outline in section 4.4.4, we assume that the capital-producing B-firms have the possibility of producing a large but also largely unknown set of capital goods. The innovative search space is to a large extent determined by the activities of the capital-using A-firms. The behaviour of the A-firms is influenced by the fact that their capital stock puts limits to their change of production routines (and increase of productivity). If the A-firms find new routines, they may not be able to implement them immediately. However, the supply of new types of physical capital from the B-firms allows using these routines. Thus, the search for better routines within the A-firms may lead to the creation of a list of routines which are not feasible in the present period. The access to such lists will radically ease the search conditions of the B-firms but at the same time an equal access of all B-firms to the lists will delimit their relevance for creating competitive advantages. However, there is not equal access to the lists, especially because they do not exist in an easily accessible form; they are difficult to establish and involve a lot of tacit knowledge. But if there is a well-established linkage between two firms belonging to the two industries, there is a large probability that the B-firm will find out about non-feasible routines of industry A. If the B-firm is also active in search of new product-variants, there is some probability that it will discover a machine-type which makes the A-routine feasible. When presented to them, the new machine will be acknowledged by A-firms as having superior characteristics and worth a higher price than ordinary machines.

However, why should A-firms allow the search in their factories for non-feasible routines? If the question should be answered in isolation and if the machine became immediately available to all A-firms, there would be no reason for helping B-firms. But B-firms may be asked whether a new routine can be performed in connection with existing machines and they may be involved in modifying existing machines. Furthermore, a new B-product is normally produced on a small scale in the beginning

and the 'linked' A-firm(s) may benefit from early access to the new machines. Such interrelations may cross national boundaries but there are grounds for believing that the probability that they are established as well as the probability that they are successful will depend on national proximity. From a modelling viewpoint these issues are worrying since they greatly complicate the tasks (not only of introducing different vintages of capital but also of creating limited access to the very last machine-type). But in principle they belong to the Nelson and Winter framework.

The two-industry framework is just one of many extensions of Nelson and Winter's conception of innovative and imitative search which allow the discussion of national systems of innovation. The importance of the national setting is considered in terms of the ease of the flow of information or the increased probability of successful products and processes. Once a national economy has embarked upon a trajectory of specialisation strong forces will be reinforcing it. Especially, the search space of the firms located inside this economy has been changed in a way which makes them relatively successful in search related to this specialisation pattern. We may think in terms of specialisation structures of two nations, the 'domestic' economy D and the 'foreign' economy F. The evolutionary argument starts in period  $t$  from the behavioural rules and the search conditions which determine the background of the competitiveness of firms and industries. Via the actual technological development of the industries (e.g., A and B), a specialisation pattern emerges which can be measured in terms of concentration or export specialisation. However, in period  $t + 1$  the specialisation structure and the related technological conditions will function as the starting point for considerations about change in the behavioural rules. Furthermore, the actual technological development in some nationally located firms and industries in one period will influence the conditions of search for other firms in the next period.

To conclude, we should note that it is through modifications of the Nelson-and-Winter framework like the ones just discussed that we are placed in a position which allows an appreciation of it. However, there is an obvious possibility that Nelson and Winter become established as 'footnote economists' who are frequently cited but not considered as related to a viable research programme. The present introduction to parts of their work is intended to suggest some ways of moving their framework from the footnotes to the main text. In particular, the programming appendix suggests explicitly and implicitly a number of tasks for future research as well as a powerful way of communicating about evolutionary mechanisms and processes.