Understanding product innovation using Complex Systems Theory.
Frenken, K.

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: http://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Chapter 9

Summary, conclusions, and further research questions

The final chapter of this study summarises the main arguments and conclusions of the study and discusses a number of issues for further research. The chapter is divided in the following five sections.

In Section 9.1, I reflect on the main contributions of this study to the understanding of technological development in general, and to the understanding of product innovation in complex systems in particular. I will go into the theoretical, methodological, and empirical contributions of this study, highlighting the synthesis of theory, methodology, and data.

Section 9.2 provides an extensive summary of the arguments made in this study. I discuss the main lines of arguments. In this summary, I follow the outline of the study in its three parts: “Part I: Formal models and appreciative theorising”, “Part II: A model of product innovation in complex systems”, and “Part III: Empirical studies of technological development”.

In Section 9.3, I list the main conclusions that have been derived from the study. A distinction is made between theoretical conclusions that have been derived from the generalised NK-model of innovation in complex systems, and empirical conclusions that are based on the results of the analysis of technological development in aircraft, helicopters, motorcycles, and microcomputers.

Section 9.4 discusses further applications of the generalised NK-model as a theoretical framework for studying technological innovation. Other possible applications cover a wide range of subjects. I will go into models of (i) the product life-cycle, (ii) the interplay between incremental, modular, architectural, and radical innovation, (iii) search heuristics, (iv) interfirm collaboration, and (v) technical standards.

In Section 9.5, I discuss a number of empirical research questions that can draw on the statistical methodology developed in this study. A number of research questions will be formulated concerning the topic of product variety and economic development. The research questions are discussed according to different levels of aggregation, and concern questions related to (i) product variety and industry development, (ii) product variety and economic growth at the national and regional level, and (iii) product variety and international trade.

9.1 Contributions of the study

The point of departure in this study is to view technologies as complex systems containing elements that function interdependently. Elements of a technology typically refer to the set of components that are incorporated in an artefact (e.g., in the case of cars, components are the engine, tires, steering wheel, springs, brakes, et cetera). Other design dimensions of artefacts can also be taken into account in the framework developed in this study such as the number of engines, wheels, gears, et cetera, and the presence or absence of a component (e.g. airbag presence or absence, air-conditioning present or absent, et cetera).
The complexity in designing an artefact stems from the interdependencies between elements in complex systems. The interdependencies or "epistatic relations" imply that the choice of one element affects the functioning of other elements. The design question then becomes in what combinations the collective functioning of elements is optimal. Therefore, the design process can be considered as a *combinatorial* optimisation problem (Simon 1962, 1969, 1973; Bradshaw 1992).

The complexity of the design process stems from the combinatorial explosion of the number of possible designs that can be assembled from a given set of elements. Let $N$ stand for the number of elements in a technology and assume that one can choose among two "alleles" per element. The number of possible designs that makes up the design space adds up to $2^N$. Thus, even for technologies containing a relative small number of elements and variants per element, the design space of possible combinations is large.

The design problem holds that optimisation by means of exhaustive search, *i.e.*, by simply testing the functionality of all possible designs and then choosing the optimal one, is very time consuming and generally too expensive. Therefore, designers are expected to follow other non-exhaustive search strategies that are less expensive but may well lead them to sub-optimal solutions.

The problem of combinatorial complexity provides the analytical basis for discussing search strategies that aim to find a reasonable solution in relatively short time. Such strategies try to reduce search time in an intelligent manner and are called *heuristics*. One well-known heuristics is local trial-and-error, a strategy that has much in common with natural selection in biological evolution (Simon 1969). This strategy holds that designers proceed by mutating randomly one of the elements in the system. If the mutation improves the technology's quality, it is accepted, and if the mutation does not improve the technology's quality, it is rejected. Variations on this strategy are based on the number of elements mutated at the same time (the "search distance").

Although trial-and-error search describes important features of technological innovation (in particular its incremental nature), and although the similarity with natural selection in biological evolution is attractive (since it allows for transfer of insights from biology to economics), it is a rather limited account of the search behaviour of designers.

In particular, I have argued that models of trial-and-error search ignore the fact that designers can use information on users' preferences. Starting from a list of functions of the technology, designers can rank the functions according to the priority that users assign to each function. Using this information of users' preferences, designers are expected to focus on mutating elements that affect the function they aim to optimise, in a sequence from most to least important function. This search strategy, which is called "function space search", is fundamentally different from trial-and-error strategy (Bradshaw and Lienert 1991; Bradshaw 1992). The latter strategy is based on random mutations in elements and is blind with respect to the function that is improved alike biological evolution, while the former strategy starts with selecting the function that is to be improved and then selects the elements for mutation.

Though substantially different, trial-and-error search and function space search can be represented and compared in the same formal model of innovation in complex technological systems. The formal model developed in this study is a generalised version of Kauffman's (1993) NK-model. The generalised NK-model describes systems with any number functions, describes selection environments with any ranking of functions, and describes any number of selection environments (*e.g.*, user groups).

---

123 Examples of alleles of elements are gasoline or electric engines, airbag present or airbag absent, *et cetera.*
Using this model, analytical insights have been derived concerning a number of issues in innovation studies, including:

- the trade-off between the number of product varieties adapted to specific user groups versus economies of scale in producing a single “dominant design”
- the potential of designing product varieties within a dominant design to realise economies of scope that stem from the common use of core elements in different designs
- the rigidity of a dominant design that, once diffused, has a capacity to adapt to changing environments without changing its core technologies

The generalised NK-model of innovation in complex systems does not only provide a formal framework to theorise about technological development, but is also consonant with combinatorial statistical methods. In this study, a statistical methodology is described that is based on entropy statistics. The entropy concept stems from the concept of a design space of all possible combinations between elements. In this state space, an individual designer “moves around” by experimenting with different combinations between variants of elements analogous to particles moving around in a state space. A population of designers (firms) that moves around in a state space makes up a frequency distribution of designs in phase space. The entropy of this distribution indicates the variety in the distribution of the population of designs. In short, entropy is at a maximum when designers would randomly move through the design space of possible designs yielding maximum design variety, and entropy is minimum when designers all choose one and the same design yielding minimum design variety.

Once it is understood that the entropy concept can be transferred to frequency distributions of technological designs, one can apply the whole apparatus of entropy methodology to data that describe product designs. These data, generally called “product characteristics”, describe each product design in terms of the combinations of elements incorporated in a design (e.g., type of engine, type of material, et cetera) and in terms of the level of functions that the design produces (e.g., speed level, safety level, et cetera). Using this data for aircraft, helicopters, motorcycles and microcomputers, entropy describes the evolution of these product technologies in terms of product variety.

The empirical analyses show that product variety stems from a branching process of different “technological paradigms” each of which is dominant in different market segments or “niches”. The number of market segments in an industry thus limits the degree of product variety. For example, four different paradigms in aircraft technology have been distinguished – piston propeller engine, turbopropeller engine, turbofan engine, and jet engine – which are dominating in different niches: business and trainer aircraft, passenger and cargo aircraft, mass-passenger and mass-cargo aircraft, and fighter aircraft, respectively. By contrast, in helicopter technology there is a single technological paradigm dominating as the creation of new niches in which new paradigms could have been developed, is inhibited by inter-technological competition with aircraft technology.

In summary, the framework developed in this thesis encompasses a theoretical model of innovation in complex systems, an entropy methodology based on combinatorial statistics, and empirical applications based on product characteristics of several technologies. The study thus provides a synthesis between theory, methodology and data. This synthesis is made possible by elaborating on the theoretical, methodological, and empirical implications of conceptualising design as a complex combinatorial problem. The main contribution of this study lies in the synthesis of theoretical, methodological, and empirical analysis of innovation in complex technological systems.
9.2 Summary

In the former section, the main contributions of this study to the understanding of technological innovation have been discussed. In this section, an extensive summary is provided of the line of argument that has been followed in the study. In the summary, I will hold on to the outline of the study in the three parts: “Part I: formal models and appreciative theorising”, “Part II: a model of innovation in complex systems”, and “Part III: empirical studies of technological development”.

In the first part, the gap between formal evolutionary models and empirical studies of technological development is described. This description led me to a list of important empirical findings that are neglected in formal models. The second part of the study takes up the challenge to develop a formal model that incorporates features of technology that have been stressed in empirical studies, but have rarely been addressed in formal models hitherto. The third part of the study develops a statistical methodology with which empirical data on four technologies are analysed.

9.2.1 Summary of Part I: Formal models and appreciative theorising

Part I of the study includes only Chapter 1. In this chapter, I reviewed a number of formal evolutionary models and a number of history-based “appreciative theories” of technological development. The main objective of this chapter has been to show that formal models of technological development, although in many respects compatible with appreciative theories, exclude a number of important features of innovation. From the reviews of formal models and appreciative theories, I listed a number of important features of technological innovation that are to be addressed in future formal models of technological development.

The chapter starts with a discussion of formal evolutionary models. These models all follow Atkinson’s and Stiglitz’s (1969) assumption of localised technological change. Under this assumption, technological change is no longer represented as a shift in the production function as a whole, as in neoclassical economics, but as efficiency improvements in the technology that is currently in use. This conceptualisation of technological development introduces time as an important variable. When technological improvements are localised in the particular technology in use, a sufficiently long period of use renders the adoption of the technology irreversible, as other technologies become obsolete. In that case, technological substitution can take place only by radical innovation that introduces a new technology on the market. The lock-in model of Arthur (1988, 1989) and the hyperselection model of Bruckner et al. (1994, 1996) can be considered as a further elaboration of the concept of localised technological development. These models show how the rate of diffusion of an individual technology can be made dependent on the number of earlier adopters reflecting increasing returns to adoption for producers and users of the same technology.

In evolutionary economics, Nelson and Winter (1982: 46) introduced the distinction between formal models and appreciative theories. Formal models attempt to describe general economic phenomena formally using mathematics and simulation techniques (e.g. growth models, competition models, and international trade models). Appreciative theories refer to broad applied frameworks that attempt to explain a particular case in full detail using both qualitative and quantitative data (e.g. industry studies, country studies).
Compared to the formal evolutionary models, appreciative theories provide a more comprehensive view on the process of technological development by classifying the evolution of technologies in particular stages of development, by distinguishing between dynamics in product and process innovation, and by looking at the co-evolution of technology and industrial structure. One of the most elaborated theories concerns the product life-cycle model as developed by Vernon (1966), Utterback and Abernathy (1975) and Abernathy and Utterback (1978). In the product life-cycle model an explorative stage, a development stage, and a mature stage are distinguished. In the explorative stage, product innovation is dominant as many firms explore the new technology in different directions. During the development stage, progressive product standardisation takes place into a “dominant design”, which triggers process innovation in large-scale production systems. In the mature stage, both product innovations and process innovations occur at a low rate, and technological development slows down until a new product life-cycle is started through the introduction of a radically new technology. The concepts of product life-cycle and dominant design share many features with the concepts in evolutionary economics of “natural trajectory” and “technological regime” introduced by Nelson and Winter (1977), and “technological trajectory” and “technological paradigm” introduced by Dosi (1982).

The formal models of technological evolution are by no means incompatible with the appreciative theories of the product life-cycle. The emphasis on the incremental nature of the larger part of technological development is consonant with Atkinson and Stiglitz’s (1969) formal concept of localised technological development. The emergence of a dominant design can be well explained by the lock-in model of Arthur’s (1988, 1989). And, successions of product life-cycles can be modelled by the hyperselection model of Bruckner et al. (1994, 1996). However, a number of issues raised by appreciative theorising have not yet been made the subject of formal models.

A first issue that is stressed in appreciative theories holds that innovation is better understood when technology is considered as a complex system of interrelated elements instead of as an input-output function (Rosenberg 1969; Sahal 1985). A second issue that is largely ignored in formal models is bounded rationality: since the outcome of design choices can not be predicted ex ante, designers use heuristics in deciding how to proceed in the design process (Simon 1969; Nelson and Winter 1977). A third issue that is generally not addressed in formal models concerns product innovation as economists tend to concentrate their analyses on process innovation. Appreciative theories of technological development have stressed the importance of product innovation for understanding the evolution of industries, including the interplay between product innovation and process innovation over the product life-cycle (Utterback and Abernathy 1975; Abernathy and Utterback 1978).

At the end of Chapter 1, the main objective of the study is formulated, which is to develop a model of product innovation in complex technological systems. This model should not follow the input-output representation of technology, but should explicitly represent a product technology as a complex system of interrelated elements. Furthermore, the output of different technologies should not be modelled as homogenous but as a bundle of quality attributes (“service characteristics”). The process of product innovation can then be understood as a bounded rational, “heuristic” search for complementary combinations of element technologies in a complex system. A technological trajectory can then be understood as the continued use of particular combinations of element technologies, and can be indicated empirically as such.
9.2.2 Summary of Part II: A model of product innovation in complex systems

In Part II, I developed a model of product innovation in complex technological systems. This model is a generalised version of Kauffman’s (1993) NK-model. The NK-model, which originated from evolutionary biology, explains the analogy between biological evolution through natural selection and human problem-solving through random trial-and-error in a formal way. Moreover, the NK-model provides a framework to address important differences between features of biological evolution and features of technological evolution.

Chapter 2 introduces Kauffman’s (1993) original NK-model of complex systems. In this model \( N \) stands for the number of elements in a system and \( K \) stands for the number of dependencies or “epistatic relations” per element. Using this model, I addressed an important difference between technological and biological evolution. Biological evolution is local in that mutations occur in single genes, while technological evolution can in principle be global in that more elements can be mutated at the same time. Using a global search strategy, which is equivalent to exhaustive search, the globally optimal design can always be found (although it generally takes many trials to find out). Therefore, the key assumption of localised technological change, which is common in evolutionary economics, requires a theoretical argumentation.

From a simulation of competing designers applying either local or global strategies, the assumption of local search is legitimised. The simulation results show that designers applying global search require much more time to find the optimal solution compared to designers applying local search to arrive at sub-optimal, but reasonable solutions. In an evolutionary environment, designers with the latter type of strategy perform better since they are able to increase the fitness of design at a faster rate, even though these designers may not be able to find the global optimum.

Chapter 3 addressed another difference between biological and technological evolution. This difference concerns the relationship between the mutation mechanism and the selection mechanism. In biological theory, mutations are modelled as occurring randomly and independent from the state of the selection environment. By contrast, human designers are able to take into account the properties of the selection environment when deciding on what element of a technology to mutate. Therefore, technological innovation can be guided by information-exchange between designers that produce new variations and users that select among variants (“user-producer interaction”).

In order to model the interaction between designers and users, I first developed a generalised NK-model in which the selection environment can be represented. The first generalisation of the model concerned the possibility to describe complex technological systems that contain any number of elements and any number of functions. Following Saviotti and Metcalfe (1984), I called the elements of a technological system “technical characteristics” that can be manipulated by producers, and I called the functions of a technological system “service characteristics” on the basis of which users select a product.

The second generalisation of the model concerned the possibility that users do not weigh all functions equally. This is generally the case as users value some service characteristics higher than other service characteristics. This generalisation was achieved by assigning different weights to the various service characteristics in the original fitness function of the NK-model. This generalisation allowed me to define user groups as consumers that apply a specific set of weights when comparing the quality of different products.
A final generalisation of the model concerns the way in which types of innovations other than mutations can be modelled. Following the classification by Henderson and Clark (1990), it has been shown how four types of innovation – modular, architectural, incremental, and radical innovation – can be represented in a generalised NK-model. All the generalisations taken together make up a generalised NK-model, or, what I have called a generalised model of product innovation in complex technological systems.

Chapter 4 reflects on the product life-cycle model, including the notions of dominant design and technological paradigm, in the light of the properties of this generalised NK-model. The central concept in this chapter is pleiotropy. The pleiotropy of an element stands for the number of functions that change when the element is mutated. Elements with high pleiotropy are elements that affect many functions and elements with low pleiotropy are elements that affect only few functions. I defined core elements as elements with high pleiotropy and peripheral elements as elements with low pleiotropy. An important property of complex systems holds that the probability of success of a mutation depends inversely on the pleiotropy of an element. The higher the pleiotropy of an element, the larger the chances of negative by-products, the lower the chances of success.

Using the distinction between elements with high and low pleiotropy, it is argued that process innovations that increase economies of scale affect product variety in a different way than process innovations that increase economies of scope. An increase in economies of scale reduces product variety as mass-products can be sold at low prices thus driving out product varieties produced in small quantities. An increase in economies of scale due to process innovation can thus explain the emergence of a dominant design. By contrast, an increase in economies of scope, for example, due to the introduction of flexible process technologies, is expected to lead to more product varieties. And, since the probability of success of a mutation is highest for low-pleiotropy elements, these varieties are expected to stem from variations in peripheral elements leaving the core elements unchanged.

The description of a product life-cycle can then be elaborated in the following way. At the start of a product life-cycle, firms concentrate on finding well working core elements. Once alleles for high-pleiotropy elements are selected, e.g. through increasing returns to adoption, a dominant design becomes established. Hereafter, innovation no longer concentrates on alleles of core elements, but on designing product varieties based on mutations in peripheral elements. The different varieties of a dominant design can be efficiently produced due to economies of scope in the re-use of one single “knowledge base” and machinery required for the production of the different varieties that are based on a single set of alleles of core elements.

The transition process between an old product life-cycle and a new product life-cycle can be understood in this model as a process of change of alleles of core elements. As explained, a mutation is a core element alone is unlikely to be successful due to the many negative by-effects a mutation in a core element generates. Therefore, a transition of product life-cycles is characterised by rapid change in many elements of the system as successful mutations in core elements require many complementary adjustments in peripheral elements. For example, the introduction of jet engines in aircraft technologies led to adjustments in many other elements in aircraft (Constant 1980).

Another important insight that has been derived from the generalised NK-model holds that a technological paradigm has a capacity to adapt to a changing selection environment by means of mutation in low-pleiotropy peripheral elements. This adaptive capacity of technological paradigms renders it difficult to introduce rival core technologies. Policies
consequences when it turns out that the existing paradigm is able to adapt by means of
mutations in peripheral elements without substitution of core elements. For example, price
policies and emission norms have not yet led to the successful introduction of alternative
group elements in many technologies, including cars (cf. Saviotti 1986; Schot et al. 1994).

The product life-cycle model including the concept of dominant design and
 technological paradigm is one out of more possible issues to which the generalised NK-
model can be applied. Other applications of the generalised NK-model are discussed below in
Section 9.4 when dealing with questions for further research.

9.2.3 Summary of Part III: Empirical studies of technological development

Part III includes empirical studies that address the evolution of different technologies in
terms of the product variety, the industrial dynamics, and the specialisation patterns of firms.
All studies are primarily but not exclusively based on entropy statistics. Entropy
measurements are used in this study to characterise the degree and nature of variety in a
distribution of product designs. Repeating entropy measurements over long periods of time
informs one about the historical pattern of technological development as expressed in the
changes in the degree and nature of product variety over time.

Chapter 5 introduces entropy statistics. It is argued that entropy is especially suited to
map evolutionary patterns of development because entropy is based on frequency
distributions only. Maximum and minimum entropy can then be considered as two extremes
of evolutionary processes. Maximum entropy occurs when designers would randomly select
the alleles for all elements leading to a maximum possible variety in designs. Minimum
entropy occurs when designers all select the same alleles for all elements. In the context of
evolving populations of product designs, entropy indicates product variety. The product
variety that actually occurs is constrained by selecting conditions such as user preferences
and economies of scale.

Entropy is not only suited to map the degree in product variety, but also the nature of
product variety using the mutual information measure.\textsuperscript{125} Mutual information is a dependence
measure that indicates to what extent different alleles of different elements are co-occurring.
For example, mutual information between the engine dimension and the wing dimension of
aircraft designs would be high when propeller engines always co-occur with straight wings
and jet engines always co-occur with swept wings (or \textit{vice versa}). The mutual information
indicates to what extent there exists clustering of designs in different “design families”. A
low mutual information value indicates the existence of one dominant family as one expects
when a dominant design emerges based on common core elements, while a high mutual
information value indicates multiple design families and the absence of a dominant design.

Patterns in technological evolution and industrial dynamics in the aircraft and
helicopter industry have been mapped using data on alleles of six design dimensions in
aircraft designs and data on alleles of five design dimensions in helicopters design. The
analysis of the aircraft industry concerns the period 1913-1984 and the analysis of the
helicopter industry concerns the period 1940-1983. The results show that the history of the
helicopter industry can be considered as a “paradigmatic” example of the product life-cycle
model. In the helicopter industry, a dominant design emerged in the fifties, a shake-out
occurred around the same time, and the degree of specialisation among firms dropped as the

\textsuperscript{125} Mutual information equals the sum of entropy of all $N$ one-dimensional distributions minus the entropy of the
$N$-dimensional distribution.

240
surviving firms were producing similar variants of the dominant design. One dominant “design family” was found that consisted of small variations of the dominant design.

By contrast, the development of the aircraft industry showed a very different dynamic. While the industry went through a shake-out around the time the alleged dominant design had been introduced (the Douglas DC-3), product variety kept on increasing and the degree of specialisation among firms increased too. These finding point to the co-existence of multiple dominant designs with different firms specialising in one of the dominant design and its associated knowledge base.

The clustering of aircraft designs resulting is concentrated in some dimensions and can be understood in the light of the generalised NK-model: particular engine types are co-occurring with particular wing types, and with lesser extent to a particular number of engines. These results suggest that important epistatic relations exist between these dimensions reflecting the trade-offs in aircraft technology. The functionality of a particular engine type depends heavily on the complementarity with the type of wings used and the number of engines used. Different combinations of alleles are used in different segments of the market in which different bundles of service characteristics are demanded. I distinguished between four families of designs on the basis of the engine type: a piston propeller family (small-size, low-speed), a turbopropeller family (medium-size, medium-speed), a jet family (small-size, supersonic-speed), and a turbofan family (large-size, subsonic-speed).

Chapter 6 concerns a second empirical study on product variety in the aircraft, helicopter, motorcycle, and microcomputer industries (Frenken et al. 1999b). This study extends the analysis in Chapter 5 in that four instead of two technologies are analyses, and two instead of one variety measures are applied. The first measure is again the entropy measure as above, and the second measure is Weitzman’s (1992) measure applied to pair-wise distances between each pair of two product designs in a product population. Concerning the technical characteristics, we used pair-wise Hamming distance and concerning the service characteristics we used pair-wise Euclidean distance. By means of measuring product variety in design space (i.e., technical characteristics) and in function space (i.e., service characteristics), we were able to link the change in technological variety to changes in product differentiation.

The results show important differences in the evolution of the four technologies. In two cases, helicopters and microcomputers, long-term variety decreased, while in the two other cases, aircraft and motor cycles, long-term variety increased. The patterns indicate that only in two out of four industries, dominant designs have indeed emerged and have led to a reduction in product variety. In the other two industries, dominant design did not occur or did not last. Instead, long-term variety increased. The results have important implications for the concept of dominant design. In the technologies we studied dominant designs appear, but they are not as dominant as implied by the initial version of the concept. For example, in aircraft several designs coexist, one in each of the niches into which the technology can be subdivided. This branching pattern, or “speciation”, can be considered as a technological division of labour, which originated historically as each design established itself in a market segment or “niche” in which it had a comparative advantage.126

126 Using data on technical and service characteristics on electric motors, Almeida (1999) also found a branching pattern of different dominant designs present in different niches. Similarly, Levinthal (1998) argued on the basis of a qualitative study that the emergence of wireless telephony is to be considered as a new branch in telecommunications technology, and labelled this development process technological “speciation”. The same argument has been made by Castro Fialho et al. (2001) regarding the technological evolution of polymer technologies.
It is argued that the evolution of technological variety can be explained by an evolutionary model that relates technological variety to the scope for niche creation (see also, Frenken et al. 2000). The scope for niche creation of a technology is expected to increase over time due to product innovations that enlarge the market for a product (e.g., faster cars, bigger cars), unless this scope for niche creation is limited by special conditions. Conditions that limit product variety, include (i) the existence of inter-technological competition between different technologies (ii) the rate of cost and price reductions, and (iii) network externalities arising from standardisation. These conditions provide an explanation why product variety in helicopter and microcomputers has decreased. In the case of helicopter technology, as explained above, the presence of aircraft technology limited the possibilities to develop new niches for helicopters at the high end. In the case of microcomputers, niches at the low-end of market did not appear due to the rapid cost and price reductions in models in the higher end of the market. Moreover, variety in computers is limited by compatibility requirements that generate positive network externalities.

Chapter 7 deals with scaling in product designs along technological trajectories in civil aircraft (Frenken and Leydesdorff 2000). In this study, a measure is proposed to indicate scaling of designs along technological trajectories over time. Scaling is indicated when two successive designs are similar in the ratios between the levels of product characteristics. This scaling measure is also applied to a whole population of products by comparing each single design pair-wise with all other designs in the population.

The patterns in scaling at the industry level show two cycles of low degree of scaling followed by a high degree of scaling. This cyclical pattern indicates two successive technological paradigms. Each cycle starts with a pre-paradigmatic stage with a low degree of scaling followed by a paradigmatic stage with a high degree of scaling. The results confirm the historical studies that have described two successive technological paradigms in civil aircraft, one based on piston propeller engine technology and one based on turbofan engine technology. The paradigmatic stages of development show a pattern of technological innovation that is characterised by incremental scaling in a series of designs starting from a dominant design (cf. Sahal 1985; Gardiner 1986a,b).

Note that the conclusion of two successive technological paradigms in civil aircraft is not incompatible with the conclusion that no single paradigm gained dominance at the level of the aircraft industry as a whole. The former conclusion refers to technological development in one market segment only, while the latter covers all segments including civil aircraft, business aircraft, fighters, bombers, cargo and trainers. An important conclusion holds that different dynamics in technological development can be indicated at different levels of aggregation.

In this study, we also showed that scaling patterns can be analysed in two time dimensions. A design can be compared to preceding designs to test for convergence of scaling patterns and a design can be compared with succeeding designs to test for diffusion of one particular scaling pattern. Each design can then be plotted in a matrix mapping the degree of scaling with preceding designs on one axis and the degree of scaling with succeeding design on the other axis. Designs that can be considered as a scaled version of preceding designs may be the designs that set the standard for future scaling in succeeding, but not necessarily so.

Dominant designs can be considered as designs that are both a scaled version of preceding designs and a design that set the stage for scaling in succeeding designs. Since dominant designs typically emerge by means of a recombination and integration of product innovations that previously were incorporated in different designs, a dominant design is a

242
design that follows on existing scaling pattern. And, since firms are expected to imitate the dominant design to profit from network externalities arising from standardisation, a dominant design is a design that sets the stage for scaling in succeeding designs.

Chapter 8 concerns the last empirical study reported in this study (Frenken 2000). In this chapter, it is shown how the original NK-model of complex systems as described in Chapter 2 can also be used to model complementarities between competencies of actors in an "innovation network". The actors that are distinguished in this study are producers that contribute with technological knowledge, users that contribute with knowledge on product requirements, and national governments that contribute with facilitating infrastructure, finance and supporting policies. Using this model, one can understand international specialisation of countries in particular technologies applied to particular markets as a consequence of interrelated and complementary strategies between producers, consumers and governmental bodies. Once joint strategies prove successful, networks are expected to stabilise.

The empirical results covering all technologies, markets and countries in the world aircraft industry, show that the degree of specialisation has risen substantially in the post-war period. Our results suggest that innovation networks as defined as successful combination between producers, users, and governments, only started after the Second World War. During the post-war period, countries increasingly specialised in developing products based on a particular technology and applied to a particular user market. In particular, new engine technologies were initially introduced in specific segments in specific countries before diffusing in other segments.\textsuperscript{127}

The analysis of specialisation patterns also puts a nuance to Vernon's (1966) international product life-cycle model. This model holds that, when product standardisation has taken place, production shifts from high-wage developed countries to low-wage developing countries. In the history of aircraft industry, developing countries indeed typically entered through the development of new aircraft models based on mature technology. However, some developed countries continued to develop new aircraft models using standardised mature technology, in particular, when demand for this technology is primarily national.\textsuperscript{128}

The study also goes into the more recent development of transnational collaborations between firms within consortia (e.g. Airbus). In the light of the NK-model developed earlier in the article, this institutional development can be understood as a means to escape historical specialisation patterns of individual countries by aligning with partners that have built up competencies in other technologies or markets. In transnational networks a new design is co-developed by the participating parties, which allows them to exchange heuristics about design, production, and marketing. I suggested that transnational networks of innovative activity could well become an important new model of technology transfer in other industries too.

\textsuperscript{127} This result is in accordance to the policy model of "strategic niche management" as proposed by Schot et al. (1994), Rip et al. (1995), and Rip and Kemp (1998). This policy model states that new technologies are most likely to be successful when initially introduced in a niche segment in which the technology is shielded from competition with established technologies used in other segments.

\textsuperscript{128} For example, American firms continued to develop new aircraft models using piston propeller engine technology and straight wings at the time that this technology is considered to have matured. These product innovations developed by American firms primarily concerned small private and corporate aircraft predominantly sold in the home market.
9.3 CONCLUSIONS

9.3.1 Theoretical conclusions

A number of theoretical conclusions from the previous chapters are listed below.

1. (Chapter 2) In the NK-model by Kauffman (1993), $N$ stands for the number of elements in a system and $K$ stands for the number of other elements that affect the functioning of an element. The K-value of a system indicates the complexity of a system as it indicates the degree of connectivity between elements.

   An alternative measure of complexity is the “cover size” of a system, which is a computational measure of the number of mutations required to find the global optimum. This number of mutations depends on the degree of decomposability of a system, which is the finest possible partitioning of a system in subsystems for which holds that no interdependencies between subsystems exist. The complexity of a system can then be characterised by the size of the largest subsystem, called the “cover size” of a system, because the size of the largest subsystems bounds the number of mutations that is required to find the optimal design.

   It is shown that the two complexity measures, the K-value and cover size, are by no means equivalent: systems with a low K-value are generally non-decomposable and thus maximally complex in terms of cover size. This means that NK-systems are generally computationally maximally complex in that the optimal design can only be found by means of exhaustive search of all possible designs.

2. (Chapter 2) For non-decomposable systems, it holds that the optimal design can only be found with full certainty by means of exhaustive search, i.e., by simply testing all possible designs and then choosing the optimal one. Exhaustive search is equivalent to “global search”, which allows up to $N$ elements to be mutated at the same time. The global search strategy can be distinguished from local search strategies that mutate less than all elements at the same time. Local search strategies are bound to end up in a local sub-optimum, but they find a local optimum much quicker than global search finds the global optimum.

   It is shown that in evolutionary environments, where competition between agents applying different search strategies takes place on current fitness and not on the fitness that would be achieved when time constraints would not matter, local search is generally more successful than global search. Local search strategies require much less time to find a reasonably fit solution and therefore tend to dominate in evolutionary environments. Local search is thus an important search heuristic as it reduces the search time without great loss of fitness of the end result. It can therefore be concluded that the assumption of local technological change in evolutionary economics as introduced by Atkinson and Stiglitz (1969) is thus legitimated.

3. (Chapter 2) Local search is a powerful heuristic in searching for fit designs of nearly-decomposable systems. Nearly-decomposable systems are defined as systems that are non-decomposable, but in which the large majority of dependencies between elements are located in subsets of elements. When nearly-decomposable systems are considered as if these subsets were decomposable subsystems, search time is greatly reduced without
great loss in fitness of the end result. This model outcome confirms Simon’s (1969) early notions on the evolutionary advantages of nearly-decomposable systems.

4. (Chapter 3) Kauffman’s (1993) NK-model can be understood as part of a more general model of complex systems as developed by Altenberg (1995, 1997). This generalised model describes systems with any number of elements in a system (technical characteristics), and any number of functions of a system (service characteristics). This model generalises the original NK-model, since the latter only describes systems in which the number of elements equals the number of functions.

A second generalisation of the NK-model is possible by specifying fitness not as the average but as the weighted average of the fitness levels of service characteristics. This means that users weigh the various functions differently. When designers have access to this information, they can search in “function space” instead of in design space (Bradshaw and Lienert 1991; Bradshaw 1992). Function space search holds that designers direct mutations to elements that are known to affect the particular function they want to optimise. It was concluded that the model of directed nature of function space search better represents human problem-solving than the model of random trial-and-error that is analogous to natural selection in biological evolution.

5. (Chapter 3) Since function space search follows users’ ranking of service characteristics, the existence of different user groups with different weights of service characteristics is expected to lead to different designs for different user groups. Put another way, product differentiation can be achieved by function space search for different user groups. Given a number of user groups, one expects the scope for differentiation to increase with the number of functions as more trade-offs are present between functions among which differentiation is possible. Furthermore, it has been derived that the scope for horizontal product differentiation depends inversely on the decomposability of a system. When a system is completely decomposable (when all elements have pleiotropy one) each element only affects one function and all functions can be optimised independently by mutations in subsets of elements. This means that whatever sequence of optimisation of functions is chosen, designers will come up with the same design.

6. (Chapter 3) The matrix classification by Henderson and Clark (1990) of four types of innovation – incremental, radical, modular, and architectural innovation – can all be formally represented in the generalised NK-model of product innovation in complex technological systems. In this classification (see figure 9-1) a “modular innovation” corresponds to a mutation in one or more alleles of elements without a change in the dependencies between elements, while an “architectural innovation” corresponds to a change in the dependencies between elements without a mutation in alleles of elements. The co-occurrence of both modular and architectural innovation is called “radical innovation”. Finally, an improvement in functions that occurs without modular nor architectural innovation is called “incremental innovation” (in the latter case, improvements stem from innovation at a lower system level, i.e., at the level of an allele of an element itself).

245
7. (Chapter 4) The pleiotropy of an element in a complex system is the number of functions that are affected by a mutation in this element. Elements with high pleiotropy are termed "core elements" in a system, since these elements affect many functions. The elements with low pleiotropy are termed "peripheral elements" in a system, since these elements only affect one or few elements. High-pleiotropy core elements and low-pleiotropy peripheral elements in technological systems are similar to core and peripheral assumptions in scientific theories (Lakatos 1970, 1978).

From the statistical properties of the generalised NK-model, it has been derived that the higher the pleiotropy of an element, the lower the probability of success of a mutation in this element. Therefore, once the alleles of high-pleiotropy core elements are selected, designers are not expected to change core elements again for long periods of time because of the low probability of success.

The fixed set of alleles of core elements characterises a "dominant design" or "technological paradigm". For example, one can speak of a gasoline paradigm in cars as the engine element is generally considered the core element. Within a technological paradigm, modular innovation is expected to be concentrated in low-pleiotropy peripheral elements, as mutations in peripheral elements have little negative effects on the functioning of other elements. Incremental innovation on the other hand is expected to take place in the alleles of high-pleiotropy core elements for two reasons. First, incremental innovations in core alleles can benefit many different designs offered by a multi-product firm as a design family has core alleles in common. Second, benefits from incremental innovation are expected to last since the alleles of core elements are seldom mutated.

8. (Chapter 4) Using one set of alleles of core elements, a single firm can develop a large range of differentiated designs adapted to very specific selection criteria. These product innovations are based on mutations in peripheral elements leaving the alleles of core elements in tact. The offering of a variety of differentiated designs can contribute to a firm's competitive advantage since a firm can profit from "economies of scope" in the production of multiple designs that are based on the same alleles for core elements. In this context, economies of scope refer to the scale economies that can be exploited with regard to the production of the same set of core elements in different product designs.

9. (Chapter 4) From the generalised NK-model, it has been derived that policies that aim to stimulate the diffusion of an alternative core technology by means of promoting particular functions (safety, energy efficiency, environmental friendliness) can well lead to
“unexpected consequences”. When particular functions are promoted that are not well met by the current dominant design, innovation will not necessarily focus on alternative core elements, but can also concentrate on peripheral elements in the existing dominant technology that relate to this particular function. For example, innovation in the car industry has been predominantly focused on peripheral elements within the existing gasoline engine paradigm, rather than on alternative alleles of the core engine element.

10. (Chapter 8) The NK-model can also be applied as a network model of epistatically related competencies of interdependent actors that cooperate in innovation projects. Using this model, one can understand international specialisation of producers in particular user markets in particular countries as a consequence of complementary competencies between producers, consumers, and governmental bodies corresponding to a local optimum. Once joint strategies prove successful, networks tend to become interlocked and specialisation patterns are reproduced over prolonged periods of time.

9.3.2 Empirical conclusions

A number of empirical conclusions from the previous chapters are summarised below. It must be stressed that the empirical conclusions are derived from analyses of a limited number of technologies. The list of conclusions is therefore tentative for what regards the evolution of technologies that have not been analysed in this study. The conclusions can therefore also be considered as hypotheses for further research in other technologies. Such issues for further empirical research are further discussed in Section 9.5 below.

1. (Chapter 5 and Chapter 6) From a review of earlier studies and from an own empirical analysis of four technologies, it has been concluded that the product life-cycle model and the concept of dominant design are too limited to account for the patterns in product innovation. Different dominant designs can co-exist in a segmented market when each dominant design is competitive within its niche. This product differentiation casu quo clustering of designs in different “families” can be understood as resulting from trade-offs between the different functions of a technology. Different user groups characterised by different sets of preferences will thus opt for different designs delivering a different bundle of service characteristics.

2. (Chapter 5) In the history of aircraft technology, during which multiple dominant designs emerged, firms tended to specialise in the production of product varieties based on one of the dominant designs. Since economies of scope are associated with the production of varieties based on the knowledge base of one dominant design, this result indicates indeed that economies of scope, though not directly measured, play a role in technological competition between firms. In the history of helicopter technology one dominant design emerged and specialisation among firms has been falling. Firms increasingly tended to produce the same varieties, which all were derived from a fixed set of core elements that make up the technological paradigm in the helicopter industry. This result also suggests that economies of scope, though not directly tested for, make up an important variable of the competitive advantage, at least in the two cases analysed here.

247
3. (Chapter 6) Differences in long-term patterns of product variety can be addressed in terms of the scope for niche creation. The larger the scope for niche creation, the larger the number of technological paradigms that can be developed, each in a different niche. The scope for niche creation is in turn dependent on the degree of inter-technological competition. When the scope for niche creation is not constrained by the presence of other technologies, i.e., when inter-technological competition is absent, product variety is expected to grow through a branching process of differentiation of technological paradigms in different market segments. When the scope for niche creation is constrained by the presence of other technologies, i.e., when inter-technological competition is present absent, product variety is not expected to grow and a single dominant design is expected to occur.

4. (Chapter 6) Two additional conditions can be specified that limit long-term product variety to increase. First, the rate in cost reduction affects the scope for horizontal product differentiation. The higher the rate in cost reduction, the larger the threat for varieties in the low-price segment to become replaced by varieties that previously were highly priced, but become quickly available at a lower price. Second, the degree of increasing returns arising from standardisation limits product variety to grow. Increasing returns render the user value of a design positively dependent on the number of other users of this design and the producer costs of a design negatively dependent on the number of other producers of this design. These two additional factors explain the fall in product variety of microcomputers analysed in this study, and the same factors are expected to operate in markets for other network products (mobile telephony, stereo components, VCR’s).

5. (Chapter 6 and Chapter 7) Different dynamics in technological development can be indicated at different levels of aggregation. At the level of an industry, product variety can increase due to speciation into different technological paradigms, while at the levels of a single market segment, a single technological paradigm tends to remain dominant. Empirical analyses of technological development and industrial dynamics should account for the existence or non-existence of different market segments reflecting user groups with different preferences and / or incomes.

6. (Chapter 7) Pre-paradigmatic stages of technological development can be indicated by a low degree of scaling in successive product designs, and paradigmatic stages of technological development can be indicated by a high degree of scaling in successive product designs. Individual designs can then be characterised in a matrix mapping the degree of scaling with preceding designs on one axis (“convergence”) and the degree of scaling with succeeding design on the other axis (“diffusion”). Designs that can be considered as a scaled version of preceding designs are not necessarily designs that set the standard for scaling in succeeding designs and vice versa. A dominant design can then be considered as a design that is both a scaled version of preceding designs and a design that sets the stage for scaling in succeeding designs.

7. (Chapter 7) Since a dominant design indicates both a convergence in scaling patterns of preceding designs and a diffusion of a scaling pattern throughout the product population in an industry, the relevant level of analysis changes during the course of a product lifecycle. Before a dominant design emerges, product development follows firm-specific scaling trajectories. After a dominant design emerges, product development follows a
collective scaling trajectory as network externalities become strong. The formulation of strategy should consequently be informed by the relevant level of analysis.

8. (Chapter 8) From the analysis of the world aircraft industry, it has been found that countries successfully introduced new technologies by means of focusing applications to a specific niche. Other countries, in particular “newly industrialising countries” typically enter by means of applying mature technologies to a niche. Both results suggest that government policy should complement the development of a specific knowledge base and the management of particular niches.

9. (Chapter 8) The analysis of countries’ specialisation patterns puts a nuance to Vernon’s (1966) international product life-cycle model. In the history of aircraft industry, developing countries entered indeed through the development of aircraft models based on old technology as predicted by Vernon. However, some developed countries continued to develop new aircraft models using standardised mature technology, in particular, when demand for this technology is primarily national.

10. (Chapter 8) The development of a new product can be organised at the national level, but also at the transnational level (e.g., Airbus). It has been suggested that transnational networks can be considered as a level at which countries that are “locked in” into a particular technology and market, can experiment with other technologies or markets. Transnational networks can be considered a new model for technology transfer compared to earlier technology transfer practices, such as licensing. Earlier practices concerned the transfer of knowledge concerning the production of an existing design, and can thus be considered as a first-order model of knowledge transfer. In transnational networks a new design is co-developed by all participants, which allows for the exchange of competencies in the development of a new design. This model of transfer can be termed second-order knowledge transfer.

9.4 FURTHER RESEARCH QUESTIONS I: APPLICATIONS OF THE GENERALISED NK-MODEL

I now turn to the discussion of further applications of the generalised NK-model of complex systems as developed in the foregoing chapters. Before discussing further applications, it must be stressed that product technology, which has been taken as the system of reference throughout this study, is one out of several systems of reference that can be modelled using the (generalised) NK-model. The formal nature of the (generalised) NK-model allows one to address different research questions related to different systems of reference. Indeed, other scholars recently applied the NK-model in domains other than in the domain of product technology. The other systems of reference concern process technologies as in the models of Auerswald et al. (2000) and Kauffman et al. (2000), and organisations as in the models of Levinthal (1997), Gavetti and Levinthal (2000), Ghemawat and Levinthal (2000), Marengo et al. (2000) and Dosi et al. (2001). A selection of these models is discussed shortly below.
Auerswald et al. (2000) and Kauffman et al. (2000) have applied the NK-model in models of process innovation. Different process technologies are described as strings of alleles of \( N \) "operations" that are epistatically linked to \( K \) other operations. Each possible string is considered as one possible process technology or "recipe" to produce a given homogeneous output. Search in "recipe space" through hill-climbing leads a firm to a locally optimal fitness peak with fitness defined as labour-costs per unit output. Thus, these studies follow neoclassical theory in defining fitness of a process technology as the efficiency at which a given homogeneous output is produced. An important result of the model of Auerswald et al. (2000) has been that the successive fitness levels attained by hill-climbing firms reproduces the logistic learning curve (Arrow 1962a).

Levinthal (1997), Gavetti and Levinthal (2000), Ghemawat and Levinthal (2000), Marengo et al. (2000) and Dosi et al. (2001) have used the NK-model in models of evolving organisations. An organisation is modelled as a set of alleles of \( N \) business policies that are epistatically related. For example, business policies include choices regarding the internal organisation, regarding product marketing, regarding delivery, regarding service, et cetera. As in the original NK-model by Kauffman (1993), evolution takes place as hill-climbing on a fitness landscape by means of local trial-and-error. This representation of organisations that evolve through trial-and-error captures the local nature of organisational adaptation. Competition between different organisations is represented by selection between different organisations according to the fitness level they attain.

I will not go further into the specifics of the models of evolving process technologies and evolving organisations because the discussion in this study is concentrated on modelling product innovation in complex technological systems. However, it is important to recognise that the (generalised) NK-model can be applied to various contexts. In principle, one can describe any system as an NK-system when the elements can take on discrete states, when the functioning of elements is epistatically related, and when the functioning of elements can be expressed by fitness, i.e., when systems are selected according to a fitness function. Whether the application of the (generalised) NK-model in a particular context produces new insights in the nature of the phenomenon in question, is specific to each application and, in my view, should be discussed in the context of the particular application. In the following, I restrict the discussion of further research questions related to the application of the NK-model to applications that take product technology as the system of reference.

### 9.4.1 A full-fledged NK-model of the product life-cycle

The first line of research in which the (generalised) NK-model can be further applied is in models of the dominant design thesis and the product life-cycle. The application of the generalised NK-model as a product life-cycle model, as I have done in Chapter 4, can be considered as a baseline model for further models. In this baseline model, I have tried to show how one can understand the interplay between process innovation and product

---

129 See also the discussion in Section 3.1 of this study.
130 Ghemawat and Levinthal (2000: 35) provide examples of policy dimensions of airlines following Porter's (1996) strategy analysis of Southwest Airlines. Examples of policy dimensions that are distinguished, are high or low aircraft utilisation, high or low frequency of departures, high or low prices, short or long distance et cetera.
131 Following the theory of local adaptation of organisations by Cyart and March (1963).
132 Following the "ecological approach" of evolving organisational structures by Hannan and Freeman (1989).
innovation in complex product technologies. In particular, I have pointed to the different effects of economies of scale and of economies of scope on the degree and nature of product variety. From the baseline model of the generalised NK fitness landscapes, full-fledged simulation models can be developed about the product life-cycle and complex product technologies. To this end, the basic model structure of search on fitness landscapes could be supplemented by (i) functions of production cost and search cost,\(^{133}\) (ii) a pricing mechanism,\(^{134}\) and (iii) a mechanism by which firms compete for profit and market shares.\(^ {135}\)

These three mechanisms have been shown to suffice to model an industry in which firms compete for market shares by means of technological innovation (Nelson and Winter 1982; Andersen 1994).

Given the many parameters in such a model, systematic simulation exercises are required to find out what parameter causes particular kinds of technological evolution and industry dynamics. In this respect, as stressed by Auerswald et al. (2000), Ghemawat and Levinthal (2000), Kauffman et al. (2000), and Marengo et al. (2000) one should start from a reference model that incorporates a minimum of specific assumptions. Using an initial setting, the effects of changes in parameters can then be assessed with reference to the model behaviour under “standard” parameter settings. The next step is thus to think of initial parameter settings. A reference model could follow the simplest of the canonical NK-model in which product complexity is absent \((K=0)\), users are homogeneous in their preferences \((G=1)\), and the number of elements are equal to the number of functions \((N=F)\).

Using the three mechanisms and the standard parameter settings as specified above, additional features can be added to represent the basic tenet of the product life-cycle model. At first instance, one can assume that economies of scale increase exogenous over time to reflect process innovation and reproduce the tendency towards product standardisation. Starting from this reference model, one can introduce systematic changes in a parameter value for \(N, K, F, \) and \(G\) to see to what extent the product life-cycle dynamics are robust. For example, for very complex technology \((high K)\) and many user groups \((high G)\), standardisation is less likely to occur.

\(^{133}\) Production costs can be specified as a function of the costs of the alleles incorporated in the design. Reductions in production costs resulting from process innovation raising economies of scale and economies of scope can then be modelled as occurring in an exogenous way. Search costs can be specified as a function of the search distance, i.e., of the number of elements that are mutated at the time. For example, one can assume that search costs increase linearly with the number of elements mutated (Kauffman et al. 2000).

\(^{134}\) From cost functions of each product in the design space, a price for each product in design space can be derived from a pricing mechanism. In evolutionary models, pricing is generally represented by a rule-of-thumb, for example, by assuming that firms determine sales price by a mark-up over total average costs (Nelson and Winter 1982). The selection environment can then be specified in terms of users that select between product design on the basis of their value-for-money, i.e., fitness divided by price.

\(^{135}\) A mechanism by which firms compete for profit and market share can be specified following Nelson and Winter (1982). One can assume that part of a firm’s profits is used to increase the production of product design that is currently offered. The rate of increase in a firm’s market share is then made dependent upon the size of profits, which will ensure that designs with higher fitness will diffuse in the market. Moreover, one can assume that another part of profits is used to perform R&D. R&D in this model concerns hill-climbing activity in search for product designs with higher fitness. In this way, new product designs are found that are subsequently introduced in the market. Note that this specification does not mean that users can select their preferred product design at all times. Even if all users have the same preference function as expressed by the weight of different service characteristics, and consequently all prefer the same design, the limited capacity of the supplying firm forces some users to adopt a second-best design. However, since the most successful firm is able to expand its capacity at the highest rate, the most preferred design will progressively become available to more users. This diffusion process continues until a firm finds an even better design through hill-climbing that subsequently diffuses throughout the market et cetera, et cetera.
Furthermore, one can introduce economies of scope in production in the model. Following the discussion in Chapter 4 of this study, economies of scope can be made dependent on the number of alleles the different product designs of a firm share. The larger the number of alleles product designs share, the larger the economies of scope that can be realised in production by a firm.

These suggestions are only few of many possible ways in which one can use the NK-model to simulate competing firms by means of technological development. In fact, there is an immense “possibility space” of simulation models based on the NK-model. As a consequence of this vast possibility space, one should limit the number of model specifications, in particular, by basing oneself on appreciative theorising. In my opinion, the development of a reference model is crucial before proceeding with the development of more complex simulation models. One can only understand the meaning of specific assumptions in complex simulation models in the light of a reference model (cf. Andersen 1994).

9.4.2 Architectural and incremental innovation

A second avenue in NK-modelling is to elaborate on the different types of innovation – modular, incremental, architectural, and radical innovation – as distinguished by Henderson and Clark (1990). In Section 3.3, I have shown how the four types of innovation can be represented in the generalised NK-model of complex technological systems. In this classification (see figure 9-1) a modular innovation corresponds to a mutation in one or more alleles of elements without a change in epistatic relations between elements, while an architectural innovation corresponds to a change in epistatic relations between elements without a mutation in alleles of elements. An improvement in functions that occurs without modular and without architectural innovation is called “incremental innovation”. And, the co-occurrence of both modular and architectural innovation is called radical innovation.

Concerning incremental innovation, it has been concluded that incremental innovation is expected to take place in alleles of high-pleiotropy core elements rather than in low-pleiotropy peripheral elements for two reasons. First, alleles of core elements are expected to be used in multiple product designs offered by a multi-product firm. Therefore, improvements made within alleles of core elements can contribute to many different designs. Second, alleles of core elements are not expected to be mutated in the short-run as the probability of successful mutation in high-pleiotropy elements is low. For this reason, R&D investments in incremental innovations in core alleles are expected to pay-off more often. The conclusion that the majority of incremental innovations is expected to take place in core alleles, is consonant with empirical examples. In several technologies, incremental improvements have concentrated in elements that are generally considered high pleiotropy core elements, for example, improvements in speed of piston propeller engines in aircraft (Constant 1980), improvements in energy-efficiency of gasoline engines in automobiles (Clark 1985), and improvements in the computing speed of processing devices in computers (Sahal 1985).

An interesting simulation exercise is to use the generalised NK-model to see whether this conclusion can be verified. A simulation model can be based on the generalised NK-model as developed in this study. In this model, firms can be modelled as being engaged in both modular and incremental innovation. One can specify one type of firms that does not direct incremental innovation to one type of elements and modular innovation to another type of elements, and another type of firms that direct incremental innovation to core elements and
modular innovation to peripheral elements. Then, one expects the more successful firms in terms of fitness to be the firms that concentrate incremental innovations to core elements and modular innovations to peripheral elements.

A second research question relates to the interplay between modular and architectural innovation. As explained above, the co-occurrence of architectural and modular innovation has been called a radical innovation. As argued by Henderson and Clark (1990), the co-occurrence of architectural and modular innovation should not be understood as accidental. The need to change some elements by modular innovation arises from the new epistatic relations imposed by an architectural innovation (cf. Sahal 1985). An example of this interplay is the development of the portable computer in which many of the existing alleles of elements used in a different architecture compared to the older desktops (architectural innovation), and in which also a number of new alleles of elements are incorporated (modular innovation). The constraints imposed by the architecture of a portable computer led to the development of flat screens as a substitute for monitor and the development of new mouse types.

In a simulation model based on the generalised NK-model, one can simulate firms that are engaged in both modular and architectural innovation. One can specify one type of firms that sequentially introduces architectural innovations and modular innovations, and another type of firms that introduces jointly architectural innovations and modular innovations. Then, one expects the more successful firms in terms of fitness to be the firms that jointly introduce modular and architectural innovation compared to firms that introduce modular and architectural innovation sequentially.

In summary, the generalised model of product innovation in complex technological systems as developed in this study provides a formal way to address the different types of innovations within one comprehensive model. In this way, one can specify search strategies that involve different types of innovation and analyse the interplay between the different types of innovations. In first instance, such simulation exercises could attempt to reproduce the stylised facts of empirical studies using a minimum of assumptions. In the longer run, simulation models may also help to formulate normative propositions regarding the expected success of different innovation strategies in different organisational environments.

9.4.3 Search heuristics

A third line of research based on the generalised NK-model as developed in this study concerns search heuristics. Heuristic search has been defined as any search algorithm that differs from exhaustive search. For example, as discussed in Chapter 2 of this study, the decomposition of a system in subsystems is a very powerful way to reduce the size of the design space whether the landscape is itself decomposable or not (Frenken et al. 1999; Marengo et al. 2000). Another heuristic is function space as discussed in Chapter 3 of this study. Function space search restricts mutations to take place only in elements that are epistatically related to a pre-selected function of the system, and the sequence of functions follows the importance that is assigned to them by users. It is important to recognise that the heuristic search strategies that have been discussed in this study are part of a larger set of heuristic strategies that agents can apply. Future research in simulation using the generalised NK-model can be devoted to enhancing the power of different heuristics in different settings.

Using the original NK-model, Gavetti and Levinthal (2000) modelled another type of heuristic that agents can apply in hill-climbing a NK fitness landscape. The agents that try to
optimise a complex system by means of hill-climbing use a heuristic that specifies a subset of the $N$ elements of the system. Mutations are allowed only in this subset of elements. In other words, it is assumed that agents do not take into account all elements of a system, but restrict mutation to take place in a subset of elements. This specification of search is consonant with the concept of "bounded rationality" that holds that designers are cognitively restricted in the number of dimensions that they can take into account in the development of a new design (Simon 1969; Allen 1994). Instead, designers apply "mental maps" that frame the high-dimensional system as a system with a lower number of dimensions. The mental map consists of the subset of elements in which mutation can take place.

The model by Gavetti and Levinthal (2000) primarily refers to organisations that try to find a successful overall business policy that consists of $N$ policies. Given their limited cognitive capacity, firms use "mental maps" to reduce the complexity of $N$ policies to a subset of policies. Following the discussion on technological paradigms in Chapter 4 of this study, the concept of mental maps is close to the concept of technological paradigm. By defining what elements are to be left untouched and what elements are promising for mutation, a technological paradigm functions as a mental map that reduces the design space of a technological system. Given the enormous size of the design space, a mental map reduces this space to manageable proportions (Allen 1994: 9; Metcalfe 1994: 935; Marengo et al. 2000: 784).

Organisations can be expected to be aware of their use of mental maps. The question becomes how organisations decide which mental map to use. By posing this question, organisations encounter a new complexity problem, since so many possible mental maps exist. One can think of a possibility space of possible mental maps. Since each element is either part of the mental map or not, the possibility space of mental maps adds up to $2^N$.

The question then becomes what type of rules agents can use to decide when to switch mental maps and in what way, and to compare the evolutionary success of different decision rules. Gavetti and Levinthal (2000) formulated three models in which agents search a given NK fitness landscape using mental maps. The three models differ in the way agents switch their mental map. The authors first formulated a baseline model in which each agent is given randomly a mental map, which is not allowed to change. In the second model, agents are again given randomly a mental map, but they occasionally change this map. In this model, the probability of switching mental maps is equal for all agents and that the choice of a new mental map in the possibility space of mental maps is modelled as random. The third model differs from the second model in that the probability of switching mental maps is inversely dependent on the fitness an agent has achieved. This assumption reflects the idea that the worse agents perform relative to the population of agents, the higher their willingness to experiment with a new mental map. In the third model, it is further assumed that agents do not choose a new mental map at random, but by means of copying the mental map of a firm that is successful in terms of fitness. This imitation strategy can be considered a "smart" strategy as agents relate the success of other agents to their mental map.

The simulation results presented by Gavetti and Levinthal (2000) show that agents the average fitness of agents in the first model is lowest and stabilises quickly once they find a local optimum. The average fitness of agents in the second model is higher than the average fitness of agents in the first model as agents in the second model are allowed to change their mental maps occasionally. The possibility to change the mental map allows agents to escape strings that were considered local optima under the previous mental map. The average fitness of agents in the third model is in turn higher than the average fitness of agents in the second
model, which shows that the use of the more "intelligent" rules to change mental maps improves the fitness of strings found in an NK fitness landscape.136

Yet another example of a search heuristic, which is related to the former one but which has not been explored so far, is the application of a mental map regarding the matrix of epistatic relations between elements and functions. This mental map does not refer to a subset of the elements that are candidate for mutation as in Gavetti and Levinthal (2000), but concerns a subset of epistatic relations between elements and functions that are candidate for architectural innovation. This mental map of epistatic relations reflects the idea that designers have some knowledge of where the epistatic relations in a complex system are located, but lack complete knowledge of the whole matrix of epistatic relations (cf. Alexander 1964; Constant 1980). The possibility space of mental maps of epistatic relations is even vaster than the possibility space of mental maps of elements, since the number of possible epistatic relations is an exponential function of the number of elements and the number of functions.137

Again, the question becomes how designers decide when to change their mental maps and in what direction.

A simulation model of evolving mental maps of epistatic relations can draw on the assumptions used in the three models of Gavetti and Levinthal (2000) regarding the evolution of mental maps of elements in a system as discussed above.138 In the first model, each agent is given randomly a mental map, which is not allowed to change. In the second model, each agent is given randomly a mental map, which is changed occasionally. The probability of switching mental maps is equal for all agents and that the choice of a new mental map is made randomly. The third model differs from the second model in that the probability of switching mental maps is inversely dependent on the fitness an agent has achieved, and in the choice of a new mental map agents imitate the most successful firms. When comparing the performance of agents applying one of the three rules, one expects again that the latter is most successful as agents can draw upon the knowledge of more successful agents by means of imitating "best practices". Another interesting research question holds from what type of learning an agent profits most. Under what conditions does it prove better to improve the mental model of the relevant elements in design space as in the first model set-up and under what conditions does it prove better to improve the mental model of the architecture of epistatic relations as in the second model set-up?

---

136 Following the model by Gavetti and Levinthal (2000), one can introduce other types of meta-heuristics regarding the way in which agents change their mental maps. For example, one can assume that designers change their mental map by local search in the possibility space of mental maps by means of only substituting one dimension at the time. This assumption reflects the idea that search for mental maps is local in the same way as search for technological design is local.

137 The number of possible mental maps of epistatic relations is derived as follows. A mental map specifies for all N elements the absence or presence of epistatic relations with at most F functions. Each function is epistatically related to at least one element in the system and at most all N elements in the system. The number of possible epistatic relations in a system thus adds up to F times (N-1). A mental map of epistatic relations specifies for each possible epistatic relation whether it is either present or absent. Thus, the number of possible mental maps adds up of $2^{F(N-1)}$ possible mental maps of epistatic relations.

138 The interest of modelling designers with mental maps of the architecture of epistatic relations is also clear from the simulation exercise in Section 2.3. In this simulation different search strategies in hill-climbing a fitness landscape of a non-decomposable, but nearly-decomposable system. The different search strategies reflect different mental maps of the same complex system. A strategy that mutates up to N elements at the time reflects a mental map of a non-decomposable system, while strategies that mutate less than N elements at the time reflect mental maps of decomposable systems. As it has been concluded from the simulation results, some of the latter strategies are more successful than the former strategy though these strategies do not correspond with the actual non-decomposable architecture of the system.
9.4.4 Inter-firm collaboration in networks

Another line of research in NK-modelling relates to the coordination of search activity when several parties work on different elements of a complex system in parallel. In this context, one can think of a spectrum of degrees of coordination in innovative activity. At the one end of the spectrum coordination is fully decentralised and at the other end of the spectrum coordination is fully centralised. The latter case of fully centralised control over the choice of allele for each element corresponds with the perspective taken in this study and in the majority of NK-models (Levinthal 1997; Auerswald et al. 2000; Gavetti and Levinthal 2000; Ghemawat and Levinthal 2000; Kauffman et al. 2000). In these models, there is a single designer that decides for all elements whether these are mutated or not, and evaluates each mutation on the basis of its effect on the fitness \( W \) of the system as a whole. In the former case of fully decentralised search, there are \( N \) agents within a firm or \( N \) firms within a group of firms, who decides to mutate its one element or not. In this case, a mutation is evaluated only with respect to the fitness \( w_n \) of a single element \( n \) (Kauffman and Macready 1995; Marengo et al. 2000; Dosi et al. 2001; Frenken 2001b).\(^{139}\) Decentralisation thus implies "anarchy" in that each agent within a firm or each firm within a group of firms is autonomous in deciding whether to mutate its own element without having any control of other elements.\(^{140}\)

To explain the difference between centralised and decentralised search in the NK-model, consider the example of a fitness landscape of \( N=3 \) and \( K=2 \) in figure 9.2.\(^{141}\) When search is centralised and takes place by means of local hill-climbing, there are to optima: strings 010 and 100. For these strings, it holds that any mutation in one element would lower the total fitness of the system as a whole \( W \). By contrast, when search is decentralised there is only one optimum: string 010. Only for this string it holds that any mutation in one element would lower the fitness value of the individual elements \( w_n \). Consequently, once the three firm have found string 010, no single firm has an incentive to mutate its own element.\(^{142}\) However, 100 would be optimal from the user's point of view, as the average fitness \( W \) of all elements is highest for this design. However, though optimal for users, design 100 will not be accepted by the firm controlling the second element, since this firm can improve its individual fitness by mutating from 0 to 1 moving from design 100 (\( w_2 = 0.5 \)) to design 110 (\( w_2 = 0.9 \)).

As shown in simulations by Kauffman and Macready (1995), decentralised control generally cannot optimise a complex system. In many cases, the strings corresponding to optima when search would be centralised, do not correspond to optima when search is decentralised. The reason that fewer optima exist for fully decentralised search compared to fully centralised search is that for strings corresponding to optima in centralised search, there

\(^{139}\) One can also interpret this model of decentralised search by different unit in a multi-unit organisation (cf. Chang and Harrington 2000).

\(^{140}\) Confer the model in Chapter 8 of interrelated competencies of producers, users and governments.

\(^{141}\) This simulation is the same as the simulation in figure 2.3-2 in Chapter 2.

\(^{142}\) This equilibrium is generally called a Nash-equilibrium. To verify whether design 010 is indeed a Nash-equilibrium, one can look at the payoffs for each firm and check whether each firm cannot improve its payoff by mutation. Payoffs are \( w_1(010) = 0.7 \) for the firm responsible for the first element (FIRM1), \( w_2(010) = 0.8 \) for the firm responsible for the second element (FIRM2), and \( w_3(010) = 0.6 \) for the firm responsible for the third element (FIRM3). A mutation by FIRM 1 would lead to design 110 and payoff \( w_1(110) = 0.5 \), a mutation by FIRM 2 would lead to design 000 and payoff \( w_2(000) = 0.1 \), and a mutation by FIRM 3 would lead to design 011 and payoff \( w_3(011) = 0.5 \).
is generally at least one firm that can improve its own fitness by mutation of its element. And, since fewer optima exist for fully decentralised search, it generally takes more mutations to find this optimum than in the case of centralised search. Another result found by Kauffman and Macready (1995) holds that, although there are fewer optima in decentralised search, the average fitness of these optima are higher than the optima found by centralised search. This result is understandable since optima in decentralised search have to meet the hard criterion that all N firms cannot improve their fitness by means of mutation of their element.

Kauffman and Macready (1995) argued that both fully centralised and fully decentralised search suffer from serious deficiencies in optimising complex systems by means of local hill-climbing. Under fully centralised search, a firm generally ends up in poor local optima as many strings correspond to locally optimal solutions with low fitness. Under decentralised search, the collective search behaviour by firms generally leads to better optima, but the search process generally takes much longer compared to centralised search. Moreover, decentralised search runs the risk of finding no optimum at all when it holds for all strings that at least one firm can improve by mutation. The main research question to be addressed thus holds whether alternative forms of coordination can be specified that can overcome the problems of decentralised control while avoiding the high search costs of exhaustive search under centralised control.

Kauffman and Macready (1995) studied a form of coordination that is intermediate between fully centralised and fully decentralised coordination. This intermediate form of coordination refers to the case in which there are several firms, each of which has exclusive control over P elements for \( I < P < N \)\(^{143} \). With regards to its block of P elements, a firm can mutate individual elements.\(^{144} \) Each mutation of one element is evaluated on the effect on all P elements controlled by a firm thus ignoring the effects a mutation might have on the other elements controlled by other firms.\(^{145} \)

![Figure 9-2: a simulation of fitness landscape of system with N=3 and K=2](image)

---

\(^{143} \)When \( P = 2 \) there is a maximum of N/2 firms all controlling two elements, and when \( P = \frac{i}{2}N \) there is a minimum of two firms both controlling half of all elements. \( P=I \) corresponds to fully decentralised coordination of innovation with N firms and \( P=N \) corresponds to fully centralised coordination with one firm.

\(^{144} \)Mutations in more than one element at the time are not allowed in this model.

\(^{145} \)Note that the patch model is formally equivalent to Kauffman's (1993) NKC-model.
The partitioning of elements over firms is called “patching” and each block of elements that is controlled by a single firm is called a “patch”. By means of tuning the K parameter, Kauffman and Macready (1995) found that patching leads to better optima compared to centralised search when $K$ is exceeding a critical value. From this simulation exercise, they concluded that when complexity exceeds a particular threshold, patching produces better results in terms of fitness than centralised search.\textsuperscript{146} Furthermore, these authors found that the optimal patch size is only a fraction of the size $N$ of the system. This result indicates that a major reduction in search time and search costs can be achieved by patching since the optimal patch size is considerably smaller than the size of the system.

Another form of coordination between firms, which has not yet been addressed in NK-models, takes the form of inter-firm networks.\textsuperscript{147} In this view, each firm controls only one element, but patches of several elements reflect collaborations between firms. When $P$ firms decide to form a network of size $P$, this implies that a mutation by one firm is accepted or rejected depending on its effect on the fitness values of all participants in the network. For example, one can assume that a mutation by one firm in the network is accepted only if no participant in the network is worse off (win-win-win).\textsuperscript{148} Alternatively, a less stringent condition holds that a mutation by one firm in the network is accepted if the average fitness of all participants increase (assuming compensation among participants). Using different rules of acceptance of an innovation of a firm in a network of firms, one can start analysing the performance of different network rules for different parameter settings $N$, $K$, and $P$ in terms of individually and collectively attained fitness values.\textsuperscript{149}

Apart from analysing the performance of different network rules given a network of particular size and particular composition of firms, one can use the model also to simulate the formation of a network. The research question becomes what type of rules can guide the decision of a firm to enter or exit a network and how do these rules perform in terms of individually and collectively attained fitness.

For example, one can specify a rule that two firms are allowed to join a network only if the two firms control elements that is epistatically related. This rule follows the NK logic that coordination is necessary only when elements are epistatically related. When elements are not epistatically related, a change in an elements does not affect the fitness value of another elements and a rationale for network collaboration is absent (agents following a “deductive logic”).\textsuperscript{150} Alternatively, one can assume that firms do not know among which elements epistatic relations are present. In this case, one can specify that firms choose partners randomly and change partners occasionally according to some evaluation rule (agents following an “inductive logic”).

\textsuperscript{146} Kauffman and Macready (1995) restricted their analysis of patches to NK-systems in which the architecture of epistatic links is determined randomly under the restriction that each element is affected by a $K$ number of other elements. It is a small step to think of powerful patches for specific architectures. In particular, following the discussion of decomposability and nearly-decomposability in Section 2.3 of this study, patches are powerful in finding solutions with high fitness, when the patches of elements correspond to decomposable or nearly-decomposable subsystems.

\textsuperscript{147} Note that this network model is different from but analogous to the network model in Chapter 8 that does not refer to collaborating firms but to collaboration between producers, users, and governments.

\textsuperscript{148} A model exercise based on these assumptions is presented in Frenken (2001b).

\textsuperscript{149} Furthermore, one can vary as an additional parameter the number of participants that is allowed to mutate its elements at the same time from 1 to $P$.

\textsuperscript{150} This rule for network formation is in line with authors who argue that one of the main reasons for firms to collaborate in networks is to exploit complementarities between their activities (Teece 1986; Nooteboom 1999).
9.4.5 Technical standards as coordination devices

Inter-firm collaboration in innovation in complex technological systems is not restricted to networks as discussed in the previous section. Collaboration can also be achieved by adopting a common standard, which renders the different elements in a system \textit{a priori} compatible (David and Greenstein 1990; Valente 2000). A technical standard mediates the interaction effects between different elements by specification of some of the properties elements have to meet to be candidate elements in a system, such as geometric forms, power voltage, computer language, \textit{et cetera}. Thus, a standard can be considered as an element in a system that does not serve a particular function as such, but serves as an interface device between other elements in a system. In this view, a standard is an element that stands "in between" other elements to ensure compatibility.

However, the representation of a technical standard in the original NK-model as an element in a complex system is problematic. As explained in \textit{Chapter 3} of this study, the original NK-model assumes that each element $n$ is characterised by an own sub-function and that the extent to which this sub-function is realised can be expressed by a value of an element's fitness contribution $w_n$. When a technical standard is represented as an element in an NK-system, it is said to serve a particular function, whereas its sole "function" is to assure compatibility between different elements in a system. The \textit{generalised} NK-model developed in this study can describe systems with any number of elements and any number of functions, and thus offers a framework in which standards can be represented. A standard in this model is an element that is epistatically related only to functions that are also affected by at least one other element. Standards can thus be considered as high-pleiotropy elements that affect many functions, but always in conjunction with other elements. Schematically, a standard can be represented as an element in an architecture in which all elements are epistatically unrelated except with the standard as in Figure 9-3.

\begin{center}
\begin{tabular}{cccc}
  n=1 & n=2 & n=3 & n=4 \\
  \hline
  $w_1$ & x & x & - & - \\
  $w_2$ & x & - & x & - \\
  $w_3$ & x & - & - & x \\
\end{tabular}
\end{center}

Figure 9-3: architecture in which epistatic relations are limited to a standard ($n=1$)

The choice of alleles of elements is thus crucially dependent on the choice of allele of the technical standard, since the functionality of each element is dependent on the joint effects of the element and the standard. As a consequence, each firm has an interest to control the choice of the standard as to maximise the complementarities between the element this firm designs and the technical standard that renders this element compatible with other elements designed by other firms.

259
Using this model set-up, one can then distinguish between two "regimes" (cf. Schilling 2000). Each individual firm can introduce a complete system design for all elements including its own standard. In this case, users are forced to purchase the complete system at one firm. Alternatively, firms may decide to collaborate in the development of one standard and to specialise in the development of one element only. Then, users can purchase individual elements at different firms that are known to be compatible. In this case, coordination between innovative activities of firms in different elements of a complex system is achieved by the common adoption of a technical standard.

Without doubt, there can be many other possible specifications of alternative forms of innovation in complex technological systems as modelled in the (generalised) NK-model. The discussion in this Section 9.4 was intended to show that the formal structure of NK-models allows one to address different forms of innovation and coordination in one comprehensive model. The issues that can be addressed in this framework include product life-cycle dynamics of innovation, the interplay between different types of innovation, heuristic search, alternative forms of coordination, and technical standards. In my opinion, the many important research issues suggest a promising research avenue in understanding complex technological systems and organisations within the framework of the (generalised) NK-model.

9.5 FURTHER RESEARCH QUESTIONS II: PRODUCT VARIETY AND ECONOMIC DEVELOPMENT

The empirical studies reported in Part III of this study showed how comparative research on different technologies enhances our understanding of technological evolution and industrial dynamics. The main novelty in these studies concerned the development and application of two variety measures, which indicate the degree and nature of variety and changes herein over time. Using data on product characteristics, the evolution of a number of technologies has been described in terms of the variety in technical characteristics space (i.e., the design space of a technology) and in service characteristics space (i.e., the function space of a technology). These analyses have contributed to our understanding of determinants of product variety, and have sharpened our insight in the specific conditions that lead to a dominant design.

An agenda for further research questions can be formulated around the central topic of variety, and in particular concerning the relation between product variety and economic development. These questions can be addressed empirically using the entropy methodology as developed in this study and the variety measure as proposed by Weitzman (1992, 1993). In the following discussion on future empirical research, I will distinguish between questions at different levels of aggregation. I start with discussing the relation between product variety and industrial development. I continue with a discussion on product variety and economic development at national and regional levels. Finally, I end with discussing questions concerning product variety and international trade.

151 Stirling (1998) developed a third measure of technological variety that is closely related to the two variety measures developed in this study. A somewhat different approach to measuring technological variety based on disaggregated differences in total factor productivity is elaborated by Cantner and Hanusch (1999).
9.5.1 Product variety and industrial development

Future research on technologies other than the ones analysed in this study is needed to assess the generality of the evolutionary patterns that were found. In particular, the hypothesis that has been put forward holds that product variety increases in the long-run unless particular conditions operate that limit product variety and lead to a dominant design. To shed more light on the generality of this model, one requires analyses of long-term product variety in many other technologies to assess under what conditions a dominant design emerges reducing product variety and under what conditions several different designs proliferate contributing to product variety.

There are many candidate technologies that are suited for this type of analysis since many products are complex assembled systems that are selected on the basis of multiple fitness criteria (e.g., power plants, engines, batteries, machinery, vehicles, furniture, consumer durables, consumer electronics, and software). However, as technical and service characteristics are generally not available from statistical offices, empirical research of this kind requires careful construction of databases covering as many dimensions and as many as product models as possible. Unconventional data sources need to be explored including volumes of consumer magazines, encyclopaedia, and archives available in firms, consumer associations, and regulatory institutions.

Future empirical research should also attempt to relate patterns in product variety to economic data on costs, prices, profits and market shares. For example, it has been suggested in Chapter 6 that the fall in product variety in microcomputers may well be related to the unknown high rate of cost reduction per unit processing power that has taken place over the last couple of decades. Only when economic data are combined with data on product variety, one can assess the evolutionary model of product variety in all its facets.

However, although economic data are available for a large number of products, the data problem in this context is to find product technologies for which both data on product characteristics are available to estimate product variety and economic data on production costs, price, profits and market shares are available. The need to find both data sources covering the same product models renders it extremely difficult to combine both data sources in empirical research. This data problem is also one of the reasons why economic data were not used in this study.

In principle, an analysis of product variety of any technology is interesting in its own right. For each technology, variety analysis provides one with a quantitative history of the technological evolution that has taken place. However, as stressed earlier, the product life-cycle model and the model of product innovation in complex system developed in this study refer primarily to the life-cycle of mass-produced, assembled end products. Therefore, hypotheses regarding the rate of product and process innovation, the development of product variety, and the industrial dynamics can not be transferred uncritically to studies of non-assembled technologies and non-consumer products.

It is interesting to analyse product variety of technologies that are non-assembled and non-consumer products to assess whether the evolutionary patterns as found for assembled consumer products also hold for other technologies (Frenken et al. 2000: 211). For example, one can distinguish between end products and intermediate products (e.g., engines, machinery). Another relevant distinction between different types of technologies is between specialised products produced in small quantities and mass-products produced in large quantities. It has been argued that in the latter case, product life-cycle dynamics are not
necessarily expected to occur. When a technology is produced in small quantities, firms benefit less from economies of scale and increasing returns of adoption (Hobday 1998).

9.5.2 Product variety and economic growth

Apart from replicating the analysis of product variety to other technologies, the variety measures can also be used to address the dynamics of economic development at levels of aggregation higher than the level of an individual industry. In the past decades, a number of scholars have attempted to relate variety to economic growth in different ways (Pasinetti 1983, 1991; Romer 1990; Metcalfe 1994a; Saviotti 1996; Weitzman 1998). In this context, it is important to distinguish between “process variety” and “output variety” (Saviotti 1996: 94-95). Process variety stands for the variety in process technologies while output variety stands for the variety in consumer products and services. Theories can then be divided in “supply side” theories that link process variety to economic development and “demand side” theories that link output variety to economic development.

Schumpeter’s (1934) notion of economic development as a combinatorial process has been an important point of departure in thinking about process variety and economic development. In this view, innovations are not to be considered as transformation of new (scientific) knowledge into new processes, products, and services, but as a largely endogenous process of creating “new combinations” from existing technologies and pieces of knowledge in new form and new context. According to Schumpeter (1934 [1997]: 68):

"The carrying out of new combinations means (...) the different employment of the economic system’s existing supplies of productive means. (...) development consist primarily in employing existing resources in a different way (...)."

The importance of combinatorial logic in technological development should not be taken to mean that “genuine” innovation by means of the introduction of new technological elements does not occur. Rather, the combinatorial nature of technological innovation in complex systems implies that new technological elements are generally introduced by combining them with pre-existing technologies (cf. Fleming 2000; Fleming and Sorenson 2001).\footnote{For example, early car development basically consisted of the introduction of engine in pre-existing carriage technologies (Rosenberg 1969).} The combinatorial and self-feeding nature of technological development has rarely been taken into account in economic growth models. As discussed in Chapter 1 of this study, traditional growth models are based on the production function concept in which technologies are described by the amount of capital and labour that is required to produce an output. In these models, technological development is modelled as an exogenous variable without specification of the underlying mechanism of technological change. The more recent “new growth theory” or “endogenous growth theory” provides more refined accounts of technological development by modelling technological development as a function of investment in research.\footnote{Discussions and reviews of these “new growth models” can be found in Verspagen (1992), Nelson (1994a), Romer (1994), and Solow (1994).} For example, in a model by Romer (1990), technological development is made dependent on the output of the research sector, where output is measured by the number of new designs for capital goods. In this model,
technological development is thus explicitly represented by process variety as measured by the number of different designs for capital goods. However, these models do not describe the development process of a new technology itself, while the interest in these models has been precisely based on the wish to understand the sources of economic development (Weitzman 1998: 332; Nelson 1994a).  

The combinatorial nature of technological development can be taken into account by evolutionary models of technological development in line with the (generalised) NK-model developed in this thesis. In evolutionary models, innovation can be considered as a mutation in some elements of a technology. When the mutated elements are substituted for alleles that already existed in other technologies, one speaks of recombination. Using the basic idea of recombination, Weitzman (1998) is one scholar who developed a model of economic growth, in which innovations build on previously developed technologies in a combinatorial way. From this basic premise, it can be derived that the scope for future technological development is a function of the present technological variety.

The hypothesis that process variety is a determinant of economic development has also been addressed in regional studies. In this context, the emphasis in research has not been on formal models, but on empirical regularities between variety and regional development. The central hypothesis in these studies holds that firms benefit from the variety in economic activities in their local environment. Hanson (2000) summarised a number of empirical studies that addressed the issue of variety with regard to economic growth and employment growth of U.S. metropolitan areas. Generally, these studies found that the variety in industrial activities within a region is positively related to employment and growth. Note that these studies use indicators of industrial variety other than the indicators developed in this study. Future regional studies on growth and employment can make use the methodologies of variety measures developed in this study.

The second line of economic models concerns the “demand side” theories that relate output variety to economic growth (Pasinetti 1983, 1991; Andersen 2001; Saviotti 2001). The main novelty in these theories is the attempt to encompass dynamics of demand. In Pasinetti’s models (1981, 1993) an economy with a constant composition of products, constant productivity growth and saturation of demand in existing products (Engel’s Law), would generate under-utilisation of resources including unemployment. Technological development in the form of process innovation that leads to productivity growth, is partly responsible for this imbalance, but technological development in the form of product innovation can compensate for this imbalance. Product innovation creates new goods and services, and therefore new sectors, which can ‘re-employ’ the resources made redundant by the imbalance arising in the pre-existing sectors.

In Pasinetti’s view, the growth in the variety of product and services in an economy, is a prerequisite for sustained economic growth and full employment in the long-run (see

---

154 One can argue that the combinatorial self-feeding nature of technological development is taken into account by increasing returns models in which previous success breeds success. However, models of increasing returns do not explicitly model innovations as arising from recombinations of existing technologies.

155 Analogous to sexual reproduction in biological evolution that recombines parts of the genes of parents (Birchenhall 1995).

156 Other models include Birchenhall (1995), Windrum and Birchenhall (1998), and Cooper (2000), which are based on a genetic algorithm that creates new varieties by recombination of parts of strings of existing varieties.

157 In the context of city development, the hypothesis that variety in economic activities contributes to city growth and development can already be found in Jacobs (1961).

158 This theory would clearly relate the rise in growth rates and employment in the OECD countries during the late nineties to the creation of many new products and services in information and communication technology.
also, Andersen 2001 and Saviotti 2001). Therefore, one expects economic growth and employment to be positively correlated with product variety at the supra-sectoral level. At the sectoral level, product variety may decline when resources from one sector are used for the creation of new products in other sectors or for the creation of a new sector. Therefore, the hypothesis of growing variety at the supra-sectoral level is compatible with a fall in output variety in particular sectors as the product life-cycle predicts (Frenken et al. 2000: 213-214). Similarly, the fall in product variety in one region of a country may free resources for the creation of new outputs in other regions of the country. The possibility of different dynamics at different levels of aggregation implies that conclusions that can be drawn for one level of aggregation cannot be extrapolated for other levels of aggregation.

The methodology of entropy statistics developed in this study and the variety measure developed by Weitzman (1992) provide one with empirical tools to address questions related to variety and economic development. Regarding the theories that relate economic growth to process variety, one can start from a baseline econometric specification that explains changes in growth by changes in process variety, both at regional and national levels. Regarding the theories that relate economic growth and employment growth to output variety, a first specification is to explain changes in growth by changes in output variety as well as to explain changes in employment by changes in output variety.

Further specification of empirical relationships may require more sophisticated data, for example regarding the nature of process variety, i.e. to what extent these process technologies can effectively be recombined. For example, measures of inter-sectoral technology spillovers can indicate the “technological distance” between sectors (e.g., Verspagen 1997). Using these distance measures, the probability of successful recombination of technology can be estimated. Equally important for further specification of empirical research questions, though, is the further development of theoretical, multi-sectoral models that attempt to sketch the basic mechanisms in which process and output variety affect economic growth and employment.

9.5.3 Product variety and international trade

A last research topic that is related to product variety and economic development concentrates on yet a higher level of aggregation, that of international trade between countries. The relationship between product variety and international trade has not yet been well studied, although such analysis may shed light on an “anomaly” found in empirical studies on trade patterns in the European Union. Contrary to the expectation that countries would increasingly specialise after the removal of trade barriers in the European Union, countries tended to de-specialisation in the period 1971-1991 (Laursen 2000; cf. Dalum et al. 1998). With the volume of trade rapidly increasing, these results suggest that intra-industry trade between countries has become more important both in absolute and relative terms.

This pattern in trade among European countries can be considered as an anomaly with regard to mainstream theory of international trade. Export specialisation is traditionally explained in terms of inter-industry trade without any reference to intra-industry trade. The neoclassical Heckscher-Ohlin-Samuelson model explains export specialisation by the relative abundance of factors of production among countries. Ceteris paribus, this model predicts increasing specialisation in exports when trade barriers are removed.

An alternative model suggests that intra-industry trade is also important, in particular when trading countries have similar abundance of factors (Krugman 1980, 1981). This model
includes product variety, which allows countries to specialise in the production of a subset of product varieties, even if countries have similar factor abundance. This theoretical model may well explain why the rapid increase in trade within the European Union has not lead to increasing specialisation patterns among its members. To test whether the volume of intra-industry trade is related to product variety, one is need of variety indicators in order to specify the volume of intra-industry trade as a function of product variety. Product variety can be indicated using the measures developed in this study.

9.6 Final remark

This final chapter summarised the main arguments and conclusions of this study. It also discussed further research questions related to NK modelling and related to the role of variety in economic development. It is hoped that this study has contributed to the understanding of innovation in general, and product innovation in complex systems in particular. Throughout the study the emphasis has been on the complexities of technological development as stressed by historians and sociologists. Recognition of complex nature of technological development poses new challenges for economic theorising. Only recently, economists have embraced complexity as a fact of everyday economic life. The difficult task has become to simulate complex phenomena using simple models that are easily understood.