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Variety and niche creation in aircraft, helicopters, motorcycles and microcomputers

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Abstract

Evolutionary theories of economic development stress the role of variety as both a determinant and a result of growth. Our empirical understanding of the role of variety, however, is still limited. We propose two variety measures, one based on entropy and one based on Weitzman's maximum likelihood procedure. It is argued that the two measures are complementary since they highlight different aspects of variety. Entropy is based on frequencies and indicates the statistical variety, while Weitzman's measure is based on the distance between products, and indicates the degree and structure of differentiation of a population. We apply the measures to product characteristics of four technologies aircraft, helicopters, motorcycles, andŽ microcomputers . The results on the three transport technologies show classic evolutionary specialisation patterns that can be. understood on the basis of niche theory. In these cases, the changes in variety are related to changes the scope of services a technology can deliver analogous to the size of a habitat of a biological species. The results on microcomputers call for another explanation, since we found that variety decreased while the scope of services increased rapidly. In this case, the rapid fall in costs per unit service decreased so rapidly that the lower end of the market continuously disappears when the higher end of the market is extended. The results on microcomputers call for extending niche theory including the rate of change in costs.

Keywords: Variety; Niche creation; Aircraft; Helicopters; Motorcycles; Microcomputers; Dominant design

1. Introduction

An important effect of economic development concerns the change in the composition of the economic system through the creation of new entities. Such new entities can be new objects Žgoods and services , new activities. Žproduction processes and

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modes of organisation. and new actors Žindividual and institutional . An important question, which can. have a considerable theoretical and policy relevance, is whether changes in the composition of the economic system are only an effect of previous developments or also a determinant of subsequent development. Considerable if not very systematic evidence exists in favour of the second interpretation. The central role played by new, high-technology sectors in the policies of industrial countries is implicitly related to the expected economic development potential of such sectors.

The role of variety is central in Pasinetti's work on economic growth and structural change Pasinetti,Ž 1981, 1993.. His central thesis holds that the emergence of new sectors can compensate for the imbalance between demand saturation and continuous productivity growth in pre-existing sectors. The resources required to perform search activities, which lead to the creation of new sectors, can only come from productivity improvements in pre-existing sectors. Thus, the emergence of new sectors and productivity growth in pre-existing sectors are complementary rather than exclusive phenomena. In this respect, Pasinetti's thesis bears a considerable similarity to that between productivity growth in agriculture and investment in the new industries during the process of industrialisation Kuznets, 1965 . Further supportŽ . for the role of variety in economic development comes from growth models that include a growth in the number of capital goods amongst the consequences of innovation Romer, 1987, 1990 .Ž .

At a lower level of aggregation, the role of product variety at the industry-level has been central to the concepts of the 'product life-cycle' and 'dominant design' Abernathy and Utterback, 1978 . Con-Ž . trary to the tendency of increasing variety at the macro-economic level, various tendencies towards standardisation can be expected to decrease variety at the industry-level. The fall in variety concerns both the technological variety and the number of firms, though only the latter phenomenon is usually supported in empirical tests ŽKlepper and Simons, 1997.. Importantly, decreasing variety at the industry level is not incompatible with increasing variety at higher levels of aggregation. Technological standardisation and productivity growth free resources which can be used to create new sectors through research and development.

In Frenken et al. 1999 , we discussed the conceptŽ . of variety in economic theory. A major problem in empirical studies on technological variety concerns the measurement of variety in product evolution. We proposed two measures that focus on different aspects of variety: the entropy measure indicating the statistical variety on the basis of frequency distributions, and Weitzman's measure which is based on a distance measure between entities. We applied them to time-series of aircraft and helicopters, which can be considered paradigmatic examples of different technological 'species' aiming at similar services. This allowed us to study the competition at the intra-technological and inter-technological level. In the following study, we elaborate on the issue of variety in a framework based on niche theory as developed in biology. We also add to our empirical analysis of aircraft and helicopters the results on two new datasets concerning motorcycles and microcomputers. On the basis of a comparison between the four technologies, it is concluded that traditional niche theory cannot explain all trends observed, and is to be extended to deal with the rate of change in costs as a result of technological improvements.

2. On the concept of variety

In the economic literature, variety is used to describe differentiation within a given product group. The type of exercises in which the concept of variety is used, such as the optimum level of product differentiation, are both static and conceived at a low

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level of aggregation, i.e., a given product class Lancaster,Ž 1975.. By contrast, an evolutionary theory deals with the interplay between variety-creation and market selection by focusing on changes in variety over time. In this context, the relevant level of aggregation is necessarily higher than has traditionally been the case in the economics literature, since its aim is to account for qualitative change, i.e., the emergence of new product classes. In biology, the concept of diversity is defined as the number of species existing in a given habitat Žsee Pielou, 1977 . This concept. bears a considerable similarity to that of variety we will develop here, though the differences between the two disciplines must be borne in mind. Thus, the concept of variety used in this paper is intermediate between the one traditionally used in economics and the one used in biology.

The biological definition of diversity implies that each time a distinguishable economic ‘species’, be it an actor, an activity or an object, is created, the variety of the economic system increases. However, this conclusion depends on the nature of variety in a way, which is more subtle than we have anticipated so far. First, the new economic ‘species’ will be clearly distinguishable from pre-existing ones only when its population is completely separated from all pre-existing populations, for example, as defined as the set represented in the characteristics space ŽSaviotti, 1991, 1994, 1996 . While this happens in. some cases, such as that of a radical innovation that is represented in new dimensions in the characteristics space, there are other ones that are expected to lead to an increase in variety, but in which the new species population is not completely separated from pre-existing ones. This problem is very similar to a long-standing one faced by biologists when dealing with speciation. Second, even admitting that two technological product populations are completely separate in characteristics space, a number of developments internal to the population can be expected to lead to a growth of variety, such as an increase in the number of entities within the population. Third, the diffusion of a new species through time also affects the composition of the economic system, although not qualitatively. Should we expect the variety of the system to change during this diffusion process? And if so, what are the determinants of increasing and decreasing variety during diffusion processes? The definition of variety previously given needs to be better articulated. In a way similar to the distinction between species and varieties, we can distinguish between inter-population and intra-population contributions of variety. Moreover, we need to pay attention to the dynamics of variety creation. We cannot expect variety to increase only at the moment a new ‘species’ emerges. The process of progressive differentiation of both new and pre-existing product populations lead to an additional change in variety.

In what follows, we apply different measures of variety to four product technologies Žaircraft, helicopters, motorcycles and microcomputers . We thus. restrict our analysis to the evolution of products, but our methodology can equally be applied to other economic entities such as actors and activities. Before describing the different measures of variety and report their results, we need to introduce in a more detailed way the concept of technological population of products. A technological population is here defined as the set of all product models of a given technology. In turn, a technology is defined on the basis of its technical characteristics, i.e., its internal structure: technologies are different when they are represented by qualitatively different technical characteristics.

Each product technology is represented by means of two sets of characteristics, describing the internal structure of the technology technical characteristicsŽ . and the services performed for its users Žservice characteristics , respectively. ŽSaviotti and Metcalfe, 1984.. The two sets of characteristics are related by a pattern of imaging, because the purpose of technical characteristics is to provide services ŽFig. 1 . Such. an approach can be considered an adaptation of characteristics approach of Lancaster Ž1966. to the study of technological innovation. While Lancaster needed only one set of characteristics because he was only interested in demand, studies of technological innovation need to deal also with the supply side. We can consider Lancaster characteristics as service characteristics representing demand, and technical characteristics to represent the supply side. Moreover, the two sets of characteristics can be conceptualised as the inner structure Žtechnical characteristics. and the interface Žservice characteristics. of the technological system, following the distinction made by Simon 1969 between the inner structure,Ž . the outer structure, and the interface or boundary of the system.

The twin characteristics framework has a number of interesting applications, since it allows us to distinguish between radical and incremental innovation, and to define elementary phenomena in technological evolution. The applications, which are of primary importance in this paper, are those to the analysis of the evolution of and competition between technological populations. Each product model is represented by a point in characteristics space. Since different models have different values or levels of characteristics, a population will be represented by a cloud, corresponding to the distribution of models in characteristics space Fig. 2 . There are three typesŽ .

$$\begin{array}{ccc} \textbf{TECHNICAL CHARACTERISTICS} & & \textbf{SERVICE CHARACTERISTICS} \\ \begin{pmatrix} X_1 \\ X_2 \\ \cdot \\ \cdot \\ \cdot \\ X_n \end{pmatrix} & \Leftrightarrow & \begin{pmatrix} Y_1 \\ Y_2 \\ \cdot \\ \cdot \\ \cdot \\ Y_m \end{pmatrix} \end{array}$$

Fig. 1. The twin characteristics representation of a product model. The double arrow between technical and service characteristics of a product represents the pattern of imaging.

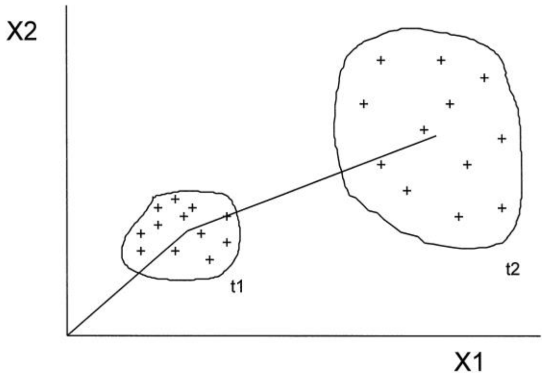


Fig. 2. Between times t_1 and t_2 the position and density of the technological population change. The center of the technological population describes a trajectory.

of changes that can take place in a technological population: first, a change in the position of the population, caused by the variation in the values of the characteristics of the models constituting the population; second, a change in the density of the population; third, a change in the number of distinguishable populations. The third type of change can take place either by means of specialisation, in which a technological population separates into two or more populations within the same dimensions of characteristics space Fig. 3 , or by means of radical innova-Ž . tion, in which one or more new populations are created in new dimensions of characteristics space. The process of specialisation and that of radical innovation creating new dimensions are amongst the most important contributors to variety growth. [3]

The distinction between technical and service characteristics, while being conceptually clear, is not always easy to apply. In some cases, the characteristics are summary variables related to both technical and service aspects of a product. And, what is considered a technical characteristic at one point in time, may acquire a meaning to consumers at a next moment in time, as it becomes closely related to

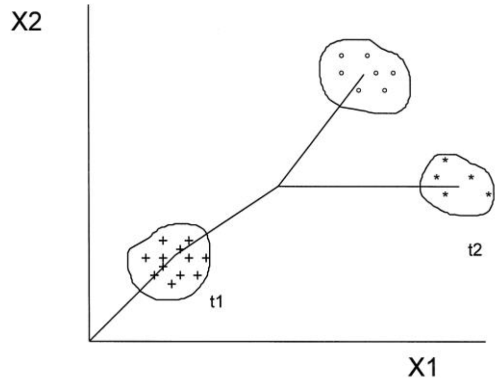


Fig. 3. Between times t_1 and t_2 technological specialization takes place, giving rise to a bifurcation in the trajectory.

particular services. In what follows, we will introduce another, but related distinction between *discrete*, *qualitati*Õ*e* variables at the one hand, and *continuous*, *quantitati*Õ*e* variables at the one hand. Discrete variables relate to qualitative design features of products and thus constitute the different product classes. In our datasets, the majority of discrete variables are technical characteristics. Continuous variables are associated with the dimensions that allow for a comparison between different product models. As such, they relate both to costs and to performance levels on which products compete and thus are closer to the concept of service characteristics.

3. Variety measures

In this section, we discuss two measures of variety, and the ways they can be applied to different types of data. The measures concern the entropy measure and Weitzman's diversity measure. The types of data concern data that are measured on discrete scales and on continuous scales. In Section 4, we apply the two measurements on empirical data on discrete and continuous product characteristics of four product technologies.

[3] In models including firm behavior and demand, technological populations are not the only populations to be considered. Populations of firms and consumers are equally important ŽSaviotti, 1998.. However, since firms compete by means of their outputs, technological populations as considered in this study play a fundamental role.

3.1. Entropy measure

The entropy value of a technological population measures the degree of uncertainty or variety in a distribution of products. The entropy measure is given by the formula (Theil, 1967, 1972):

$$H(X_1) = \sum_{i=1}^{A} p_i \log_2(1/p_i) \qquad (i=1,\ldots,A) \qquad (1)$$

where p_i stands for the relative frequency of products classified in class i along product dimension X_1, and A to the total number of classes along dimension X_1. The logarithmic can be two for variety in bits or the natural logarithm for 'nits' (here, we use bits). The measure applies to data that are classified in discrete classes in which each datum is exclusively assigned to one of the classes. For example, a technological population can be described by its distribution among the engine characteristic (gasoline, steam, electric, etc.). The entropy measure has a minimum value ($^2\log 1 = 0$) when all observations lie in one and the same class. In that case, there is one class i for which holds $p_i = 1$. The maximum entropy value equals $^2\log A$ when all observations are equally distributed among the classes. Then, all classes have the same relative frequency equal to $p_i = 1/A$. Thus, the maximum entropy is solely dependent upon the number of classes A reflecting the idea that the number of distinguishable technological classes bounds the total possible variety.

The entropy measure for multivariate frequency distributions along dimensions X_1, X_2, etc., is given by:

$$H(X_1, X_2, \ldots) = \sum_{i=1}^{A} \sum_{j=1}^{B} \ldots p_{ij\ldots} \log_2(1/p_{ij\ldots})$$

$$(i=1,\ldots,A;\ j=1,\ldots,B;\ldots) \qquad (2)$$

The minimum multivariate entropy equals zero and the maximum entropy equals $\log AB\ldots$ The multivariate entropy value measures the joint variety along several dimensions. An important drawback of the entropy measure on product characteristics is that it cannot be applied in a straightforward manner to continuous product characteristics. The entropy measure can only be applied to data that are classified in classes of observation. Along continuous dimensions the choice of the number of classes, their width, and the tail of the distribution involves decisions that remain to some extent arbitrary.[4]

[4] For applications of entropy in continuous space, see Theil and Fiebig (1984).

Example

The entropy formula can be applied to distributions of discrete characteristics in a straightforward manner. We give an example here of a technology described in terms of two characteristics. On the basis of the matrix of joint relative frequencies, one can compute the univariate entropy values $H(X_1)$ and $H(X_2)$ using formula (1), and their joint entropy value $H(X_1, X_2)$ using formula (2).[5] Consider the following observations on two characteristics of four aircraft models in Table 1. The univariate entropy values are:

$$H(X_1) = 0.5\ {}^2\log 2 + 0.5\ {}^2\log 2 = 1.00$$

$$H(X_2) = 0.25\ {}^2\log 4 + 0.75\ {}^2\log(4/3) = 0.81$$

And, the multivariate entropy equals:

$$H(X_1, X_2) = 0.25\ {}^2\log 4 + 0.25\ {}^2\log 4 + 0.5\ {}^2\log 2 = 1.50.$$

The bivariate entropy is smaller than its maximum entropy of an equiprobable distribution which equals $^2\log AB = {}^2\log 4 = 2$. The reason for this result is the relative density of aircraft incorporating a turboprop engine and a swept wing.

3.2. Weitzman's measure of diversity

The measure of diversity of Weitzman (1992) is based on a maximum likelihood grouping procedure using some distance measure 'd' which measures the degree of dissimilarity between two members in a population. In the following, we use a notation in which *x* and *y* stand for different members of a population Ž *x* should not be confused with X_1 and X_2 which stand for the product characteristics in which all members of a population are classified ..

5 It can be shown that the bivariate entropy value is either smaller than or equal to the sum of the univariate entropy values. The difference between the bivariate entropy *H*ŽX ,$X_{1\ 2}$. and the sum of the univariate entropies *H*ŽX_1. and *H*ŽX_2. is known as the expected mutual information, and serves as a measure of dependence or correlation. The formula for the mutual information is given by: *T*ŽX ,$X_{1\ 2}$.s *H*ŽX_1.q *H*ŽX_2.y *H*ŽX ,$X_{1\ 2}$.G0. For an axiomatic treatment, see Theil Ž1972.. See also Leydesdorff Ž1995 ..

The distance measure needs to satisfy the following conditions Weitzman, 1992 :Ž .

*d x*Ž ,*y*.G0 Ž .3

*d x*Ž ,*x*.s0 Ž .4

*d x*Ž ,*y*.s*d y*Ž ,*x*. Ž .5

For a set *S* not empty, the value *V S*Ž . of the diversity of *S* is the solution of the recursion:

*V S*Ž .s max Ž*V S*Ž _*y*.q*d S*Ž _*y*,*y*.. Ž .6
*y*g*S*

where *S*_*y* stands for a set *S* without product *y* and *d S*Ž _*y*,*y*. for the distance between this set with product *y*. The solution of the recursion is unique once the initial conditions, *V x*Ž .'d_0, ; *x*, are specified for any d_0 Žwe simply take d_0 s0.. This formula holds that the diversity of a population is the maximum, over all members in the population, of the distance of a member from its closest neighbour, plus the diversity of the population without that member. Weitzman 1992 showed that this measureŽ . has the logical properties that are usually associated with diversity, and thus constitutes a useful measure from a pragmatic point of view for more details, seeŽ Frenken et al., 1999 ..

A crucial aspect of Weitzman's measure is the choice of distance measure. In general, different distance measures will generate different diversity values for the same set. An appropriate distance may vary for different applications. In the case of discrete characteristics, the distance between two products can be calculated as the Hamming distance. This is simply the number of discrete characteristics in which two products differ Žcf. Weitzman, 1993; p. 165 .. For example, following the data example given in Table 1, the Hamming distance between the first and second product equals one since the two products differ only with respect to the wing characteristic, while the Hamming distance between the first and third product equals two since these two products differ both with respect to the engine characteristic and with respect to the wing characteristic.

Table 1
Data example of discrete product characteristics

	X : Engine type$_1$	X : Wing type$_2$
Product 1	jet	delta
Product 2	jet	swept
Product 3	turboprop	swept
Product 4	turboprop	swept

Table 2
Data example of continuous product characteristics

	X : Engine power kW$_1$ Ž .	X : Speed km$_2$Ž rh.
Product 1	1000	60
Product 2	1500	200
Product 3	1200	220
Product 4	5000	400

Here, we give a more elaborated example of the Weitzman measure applied to continuous data, and we explain the different stages in the calculation of Weitzman's diversity measure. In the case of continuous data, the distance among two observations can be measured in Euclidean space. The Euclidean distance between products that are described by multiple product characteristics, can be calculated using Pythagoras' formula. However, distances in a multidimensional Euclidean space are dependent upon the unit of measurement kmŽ rh, milesrh, etc. . For this. reason, one usually normalises the univariate distance using the mean value cf. Saviotti, 1988 . SoŽ . we have for the multivariate case:

$$D(x,y) = \sqrt{\left(\frac{X_{1x}-X_{1y}}{\sum X_1/N}\right)^2 + \left(\frac{X_{2x}-X_{2y}}{\sum X_2/N}\right)^2 + \dots} \qquad (7)$$

for sets containing N observations.

Consider the following observations on two characteristics of four aircraft models in Table 2. Using formula (7) we can calculate the pair-wise normalised Euclidean distance for the product population. The results are given in Table 3.

To calculate the diversity in the set of observations we apply to this matrix Eq. (6), following the 'Theorem of fundamental representation' (Weitzman, 1992) that allows to reduce the number of

Table 3
Matrix of normalised Euclidean distances

	P1	P2	P3	P4
P1	0			
P2	0.677	0		
P3	0.733	0.165	0	
P4	2.402	1.848	1.929	0

operations. The first step is to look for the two products that are closest in the set P1,...P4 which 4 are P2 and P3 having a distance equal to 0.165. Then, the value of the diversity is given by:

*V*ŽP1,P2,P3,P4.smaxŽ Ž*V* P1,P2,P4 ,.

*V*ŽP1,P3,P4..q*d*ŽP2,P3.

The respective matrices of the two subsets are given in Table 4.

Then, we repeat the procedure for the two subsets:

*V*ŽP1,P2,P4.smaxŽ*V*ŽP1,P4 ,. *V*ŽP2,P4..

q*d*ŽP1,P2. s*d*ŽP1,P4.q*d*ŽP1,P2.

s2.402q0.677 s3.079

*V*ŽP1,P3,P4.smaxŽ*V*ŽP1,P4 ,. *V*ŽP3,P4..

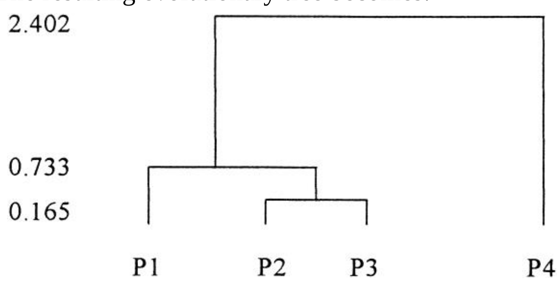
q*d*ŽP1,P3. s*d*ŽP1,P4.q*d*ŽP1,P3.

s2.402q0.733 s3.135

The maximum likelihood recursion of the matrix of Euclidean distances then adds up to:

*V S*Ž .s0.165q2.402q0.733s3.300

The resulting evolutionary tree becomes:



Weitzman's measure thus indicates the most likely structure of differentiation within a product population based on some measure of distance between products. The crucial difference of the entropy measure with Weitzman's measure holds that the former takes into account the relative of frequency of product variants while Weitzman is solely based on their distance. Therefore, the two variety measures are *complementary* as they indicate different aspects of variety related to different subject matters. Entropy is especially indicative for standardisation trends since the lower the entropy value of a distribution, the higher the skewness of the distribution. Thus, entropy measurement is particularly informative with regard to the emergence of a dominant design, which leads to lower entropy values. Weitzman's measure deals with the degree and structure of differentiation within a population. The measure is based on a notion of distance between different products, and thus indicates the extent in which products are localised in niches in characteristics space.

Table 4
Subsets of original matrix in Table 3

	P1	P2	P4		P1	P3	P4
P1	0			P1	0		
P2	0.677	0		P3	0.733	0	
P4	2.402	1.848	0	P4	2.402	1.929	0

Note that, in principle, Weitzman's measure of a product population may be high when the entropy value is low. This is the case when a single design dominates the population, but alternative designs survive in regions in the characteristics space that lie very far from the dominant design. Weitzman's measure may also be low when the entropy is high. This is the case when many product designs co-exist which have more or less equal shares in the population, but which lie very close to another.

The repetitive procedure underlying Weitzman's measure of breaking up sets into subsets implies that the computing time doubles for each observation added. This exponential growth in computing time limits the application of Weitzman's measure to small datasets given the state of current computing technology maximum about 25 observation . There-Ž . fore, in the following, we are forced to work with relatively small sets.

4. Application and results

We applied the entropy measure and Weitzman's diversity measure to four databases containing discrete and continuous product characteristics. The data concern 731 aircraft models years 1913–1984 ,Ž . 144 helicopters years 1940–1983 , 80 motorcyclesŽ . Žyears 1911–1996 and 4917 microcomputers years. Ž 1983, 1984, 1988, 1992–1997.. The description of the data including their sources is listed in Appendix A. Each product is assigned a date corresponding to its year of introduction. Information on the year of its removal and its sales in between the year of introduction and removal is lacking, so we are forced to measure variety on the basis of new products per period considered. Thus, the product population concerns the distribution of product characteristics of new product offerings. Our variety measure thus focuses on the *technological eÕolution* of an industry as expressed in changes of product characteristics in new product models over time and not on the industrial evolution in terms of market shares Žsee also, Frenken et al., 1999 ..

4.1. Periods with constant number of obserÕations

The number of new products introduced per year differs greatly for all our datasets. Thus, the distribution of new product offerings is not uniform in time. However, to analyse the change of variety of a product population over time, we preferably deal with periods containing the same number of observations, since the Weitzman measure is sensitive to the number of observations. For each observation added to the set, which is different from other observations in the set, the Weitzman measure increases. Therefore, we divided the data sets chronologically in periods containing the same number of observations *N*. By keeping the number of observations constant per period, we are able to measure the changes in variety which are due to the changes in the *composition* of a population which interests us here. By doing so, we normalise for variety effects caused by the number of observations per periods. This is another way of saying that we are interested in variety in *eÕent time* instead of in *real time*, since updates in technological systems are constituted by the events that take place within the system cf. theŽ lock-in model, Arthur, 1989 . We thus take as events. the introduction of new product models.

The need for normalisation poses a problem since the constitution of chronological periods of *N* cases often requires that we assign data within a single year to different periods. For example, if we would have 12 observations in year 1901 and eight observations in year 1902, and if we would want to constitute two periods each containing ten observations Ž*N*s10., then we need to assign two observations of year 1901 in the second period. To avoid underand over-estimations, we divided the data several times by random assignment five times for aircraft,Ž three times for helicopters and motorcycles . Since. the computing time needed to calculate Weitzman's measure grows exponentially with the number of observations, we are forced to work with relative small number of observations per period. [1] We have chosen *N*s17 for aircraft yielding 43 periods, *N*s 12 for helicopters yielding 12 periods, and *N*s10 for motorcycles yielding eight periods. In the following, we plot variety values per period and not per year.

The data on microcomputers poses an another problem since the number of observations per year is over 100 observations, while the computing requirements of Weitzman's measure are only practical for a maximum number of about 25 observations. For this reason, we are in need of a representative sample of the observations of microcomputers for each year. This has been done by the following procedure: first, we calculated the average Euclidean distance between all observations. Then, we ranked the observations by their average Euclidean distance from the lowest distance to the highest distance. Thus, we have a ranking of products from product models that are on average very similar to the rest, up to product models that are on average very dissimilar to the rest. Then we divided the rank distribution in 17 groups, and picked randomly one observation from each group. This procedure has been repeated three times, thus yielding three samples for each year. So, we have three samples of *N*s17

[1] The calculation takes 10 s for 17 observations. For each observation added computing time doubles.

microcomputers for each year. Different from the data on the other three technologies, we can list the variety values of microcomputers per year and not per period.

4.2. Results

Four each of the four technologies, the entropy of discrete product characteristics and the Weitzman measure of discrete and continuous product characteristics have been calculated. In total, we obtain

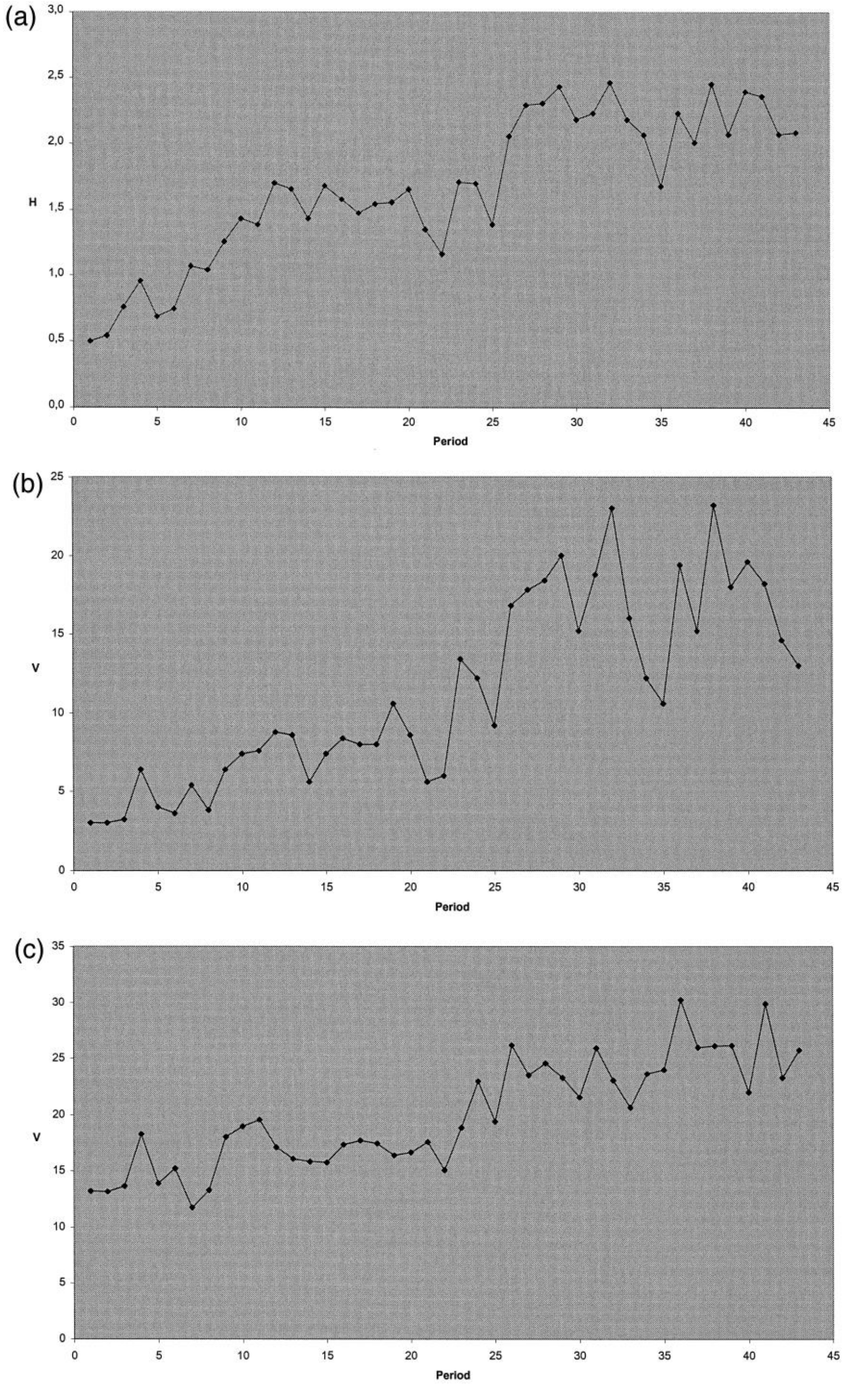


Fig. 4. a Entropy value on discrete variables of aircraft. b Weitzman's measure on discrete variables of aircraft. c Weitzman's diversityŽ . Ž . Ž . measure on continuous variables of aircraft.

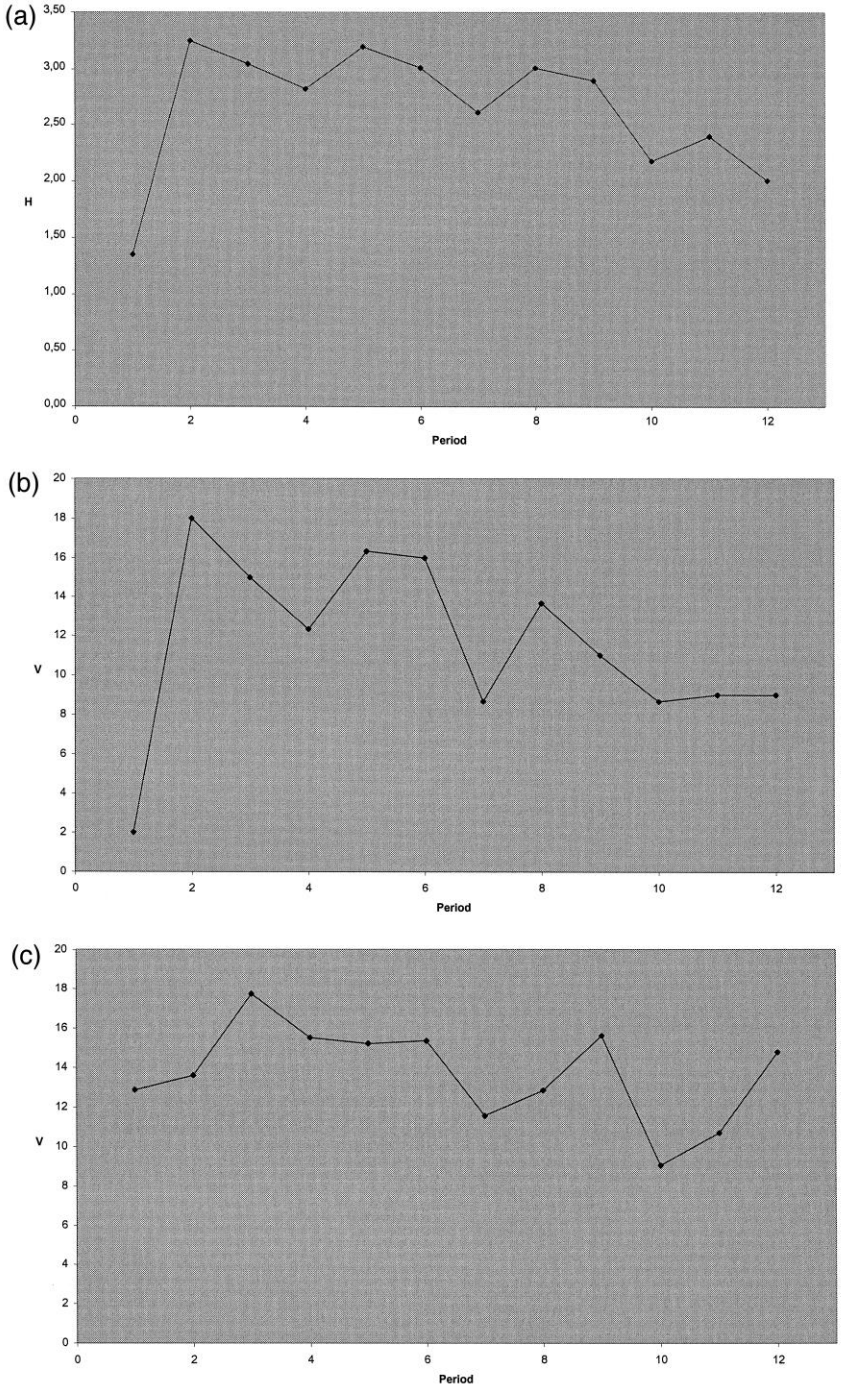


Fig. 5. a Entropy on discrete variables of helicopters. b Weitzman's measure on discrete variables of helicopters. c Weitzman's measureŽ . Ž . Ž . on continuous variables of helicopters.

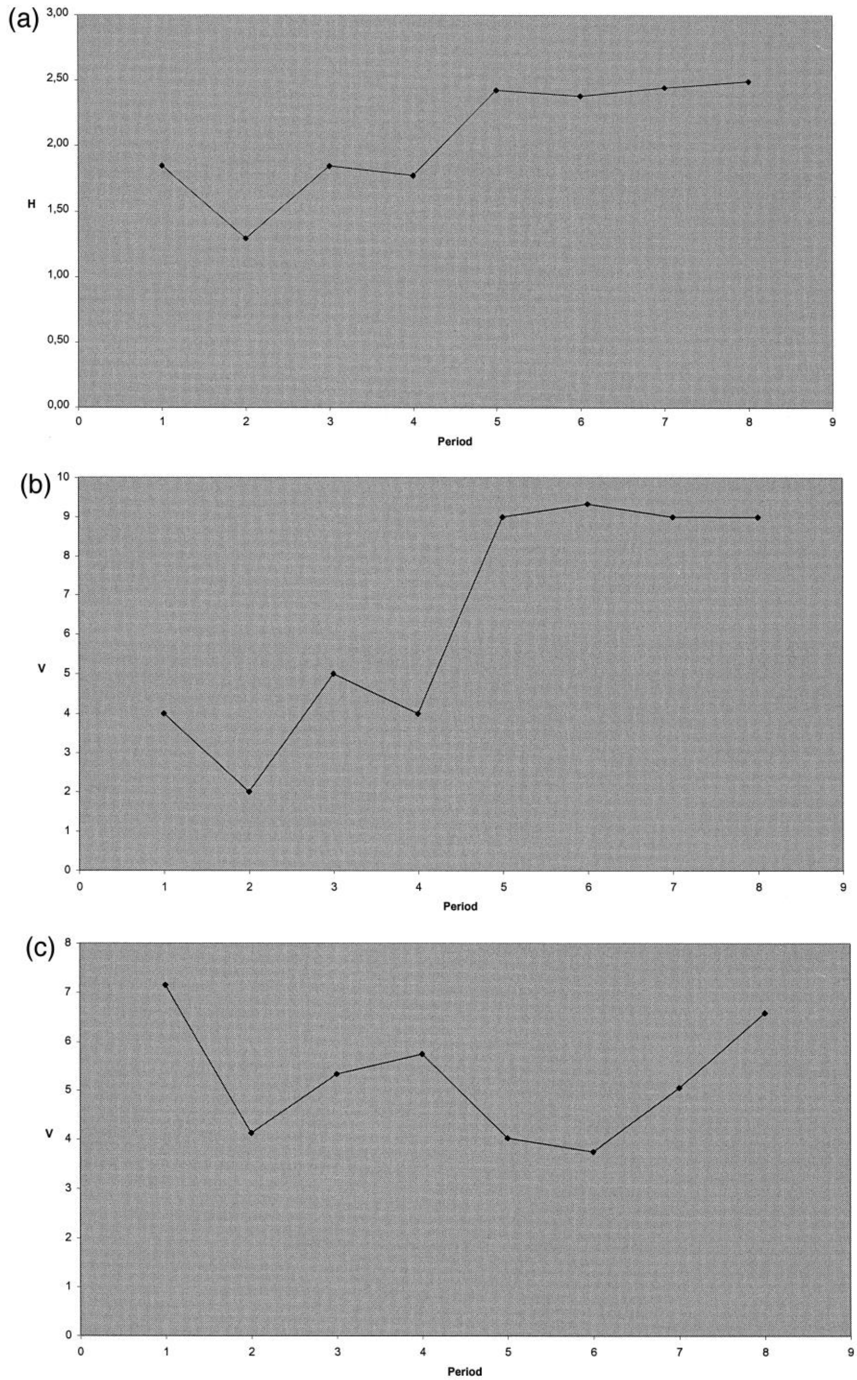


Fig. 6. Ž .a Entropy on discrete variables of motorcycles. bŽ . Weitzman's measure on discrete variables of motorcycles. cŽ . Weitzman's measure on continuous variables of motorcycles.

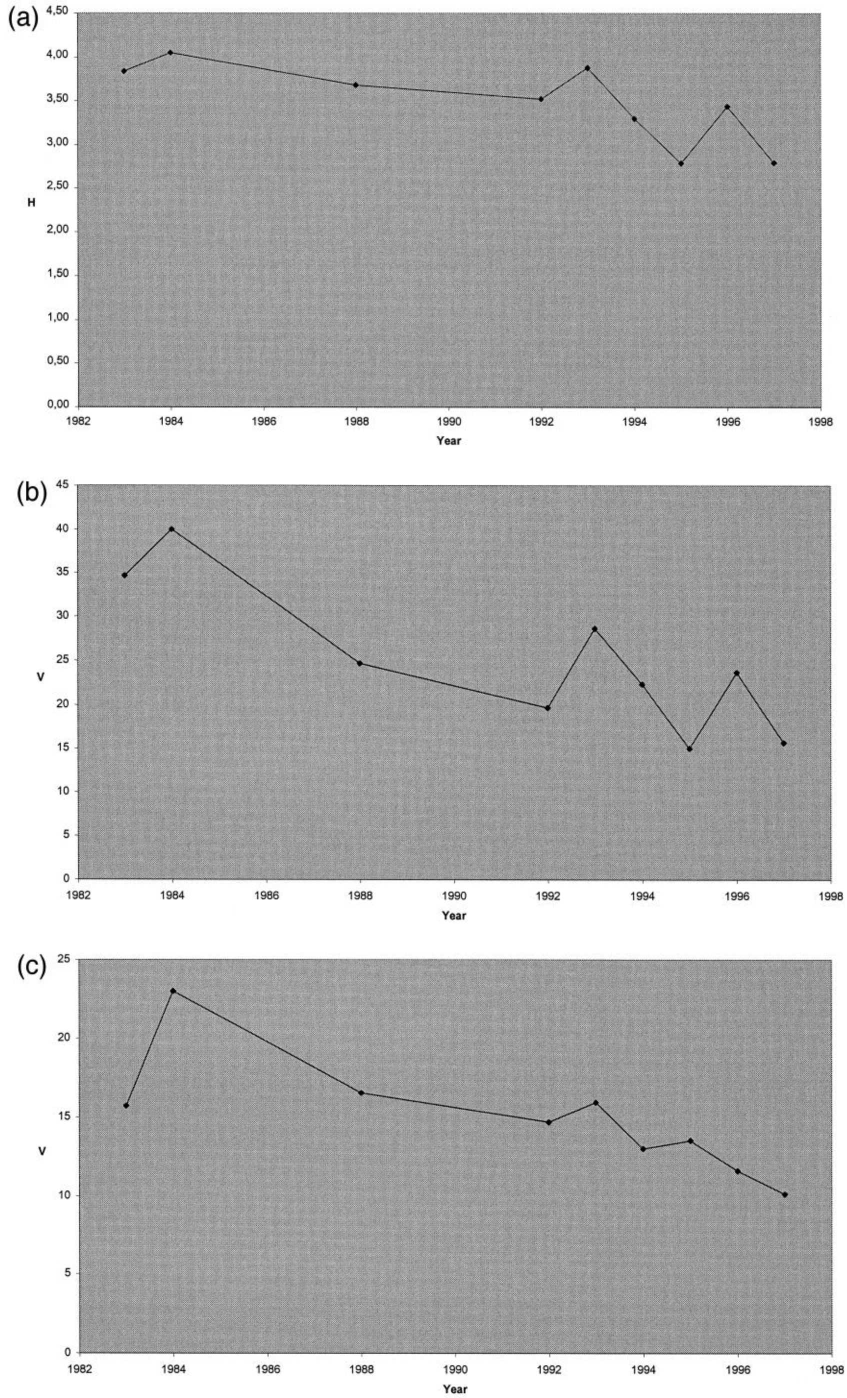


Fig. 7. Ž .a Entropy on discrete variables of microcomputers. Ž .b Weitzman's measure on discrete variables of microcomputers. Ž .c Weitzman's measure on continuous variables of microcomputers.

12 graphs. The three variety measures on aircraft data are listed in Fig. 4 a–c , on helicopters in Fig.Ž . 5Ža–c , on motorcycles in Fig. 6 a–c , and on micro. Ž . computers in Fig. 7 a–c . Note that in the case ofŽ . aircraft, helicopters and motorcycles, the variety is plotted per period and not per year. The years that correspond to each period are listed in Appendix B. The main result holds that for all four technologies, the long-run trends indicate a clear direction in the variety trends: for helicopters and microcomputers decreasing variety, and for aircraft and motorcycles we find increasing variety except for the continuousŽ data on motorcycles . These pronounced differences. suggest that the various determinants of variety are to a large extent industry-specific.

The decreasing trends in variety in Figs. 5 and 7 point product standardisation in helicopters and microcomputers. Thus, with regard to these technologies, the results do not contradict the emergence of a dominant design. Product characteristics of helicopter and microcomputers tend to converge both in terms of their frequency distribution as indicated by the entropy, and in terms of their differentiation structure as indicated by Weitzman's measure. The results on helicopters correspond to earlier findings of a study by Saviotti and Trickett 1992 which wasŽ . based on different measurements.

By contrast, the results on aircraft and motorcycles suggest that standardisation trends have been only temporary. The overall rising trend does not imply that variety has not been decreasing at particular stages of development. In Fig. 4 on aircraft variety, we find a slightly decreasing trend around periods 12–22, which corresponds to the years 1933–1942. The Douglas DC3 introduced in 1936 may well be responsible for this trend as it is commonly viewed as the dominant design in the history of aircraft Miller and Sawers, 1968; Constant, 1980 .Ž . In Fig. 6 on motorcycles, we find the lowest variety values for period 2, which corresponds to the period 1937–1949. Again, this may point to the short period of standardisation related to the emergence of a dominant design in the late thirties Žnotably, the Triumph Twin Speed introduced in 1937, see Brown, 1996 ..

The general results thus support the dominant design thesis, but they also show that the decrease in variety as a result of a dominant design has been only a temporary phenomenon in the history of aircraft and motorcycles. In these cases, the emergence of a dominant design has been of limited impact on the future course of technological development. Therefore, even if dominant designs are found to be a general phenomenon in technological evolution, its impact on the future course of product development and variety is to a large extent indeterminate. [2] The dominant design thesis is thus to be extended with theoretical propositions regarding the dynamics of product competition over long periods of time.

5. Niche theory

The differences in the trends of variety in the four technologies suggest that the evolution of variety is rather specific to particular features of a technology and its market environment. In order to understand these differences, we need to introduce some considerations about the dynamics of the emergence and development of technological populations. According to a model of technological evolution based on replicator dynamics ŽSaviotti and Mani, 1995; Saviotti, 1996 the rate of creation of new technolog-. ical populations is proportional to the volume in service characteristics space of a pre-existing population. The volume in service characteristics space is a measure of the scope of the technology, that is, of the range of services it can perform. A technology can be expected to split into a number of niches proportional to the width of the range of services it can provide, corresponding to a process of specialisation. Increases in variety can thus be considered as a form of technological division of labour.

This result corresponds to the predication by niche theory in biology, according to which the number of niches that can be created in a given habitat is

[2] A period of temporary standardization within a dominant design, and a subsequent increase in technological variety has also been found for agricultural tractors on the basis of a descriptive statistic Saviotti, 1996 .Ž .

proportional to the size of the habitat May, 1973 .Ž . Of course, we do not expect niche theory to apply unchanged to an economic environment. However, the idea that the number of niches is proportional to the range of services performed seems rather intu-

itive. Indeed, the range of services provides us with a measure of the differentiability of a given product technology. However, we will later see that niche theory needs to be adapted in order to explain all results obtained in this paper.

5.1. Aircraft, helicopters and motorcycles

The differences between trends in aircraft variety in Fig. 4 and helicopter variety in Fig. 5 can be understood on the basis of niche theory. The ranges of services provided by aircraft e.g., ranges of speed,Ž of maximum take-off weight and of range are much. wider than those provided by helicopters. The range of helicopter technology is currently limited to speed levels of about 350 kmrh, and flight range of about 1200 km. Thus, while the aircraft industry can specialise and form niches Že.g., high-speedrlowpayload, low-speedrhigh-payload, etc. , helicopter. industry is already a niche. Importantly, the possibilities to increase the range of services of helicopters are limited by the presence of relatively cheaper aircraft technology in the ranges of services above those of helicopters Taylor, 1995 . Thus, the limitedŽ . variety in helicopters can be partly explained by the inter-technological competition between aircraft and helicopters.

From the niche-theoretical framework, it can be derived that the emergence of a dominant design in aircraft cannot be expected to reduce technological variety per se when this dominant design leads to rapid increases in the range of services a technology can supply. Closer examination of aircraft data reveals that designs are at best dominant in a given subset of the technology, which corresponds to particular niches. 'Turbofanqswept wing' predominates in medium-speed, long-distance, high-payload aircraft, 'turbojetqdelta wing' predominates in high-speed, medium-distance, low-payload aircraft, and 'turbopropqstraight wing' predominates in low-speed, short-distance, low-payload aircraft. Thus, a dominant design is specific to particular niches in characteristics space Frenken et al., 1999 . Further-Ž . more, even within helicopter technology the most frequent design being the design incorporating two turboshaft engines and one rotor, is dominant only in a statistical sense. A subset of the technology, large military helicopters, has a different design incorporating two rotors. However, such a type of helicopter is developed only in very small numbers and thus not influence importantly the variety values.

With regard to the changes in variety of motorcycles, the trend is most pronounced for discrete characteristics in Fig. 6 a–b . The Weitzman measure onŽ . continuous characteristics of motorcycles in Fig. 6 cŽ . shows a cyclic pattern. In this figure, we find that at two stages of development, variety falls in period 2Ž and periods 5–6 , while in the last two periods. variety increases rapidly again. This is an interesting result since it shows that the continuous and discrete variables of motorcycles can behave differently in the course of time. Such a difference is understandable if we take into account that discrete variables often measure the presence or absence of a certain design feature. In this case, the changes in design features are not necessarily accompanied by a change in variety of a continuous variable measuring the level of related service of the corresponding design feature. Thus, to the extent that new features are added to the technology, the variety as measured by discrete variables may increase. At the same time, the continuous variables related to the performance level of services may decrease if the performance of technological models converges, even when a greater number of design features have become available. Alternatively, this result may point to an omission of some important continuous characteristics to which design features may be related, such as the noise level, acceleration capacity, and fuel efficiency.

The two drops in the Weitzman measure on continuous characteristics of motorcycles in period 3 and periods 5–6 correspond to the years 1956–1961 and 1969–1985. During these two periods, a strong standardisation tendency took place in power and speed. In period 3, the majority of motorcycles concerned models with a power level around 50 hp and a speed level around 150 kmrh. And, during periods 5 and 6, the majority of motorcycles concerned models with a power level around 100 hp and a speed level around 220 kmrh. Interestingly, after period 6, variety in continuous characteristics increased rapidly again, as light four-stroke models found a niche at the lower end of the market low-Ž power, low-speed . These models are typically used. for short-distance transport in cities. Other niches concern heavy, medium-speed four-stroke models for long distance transport, and the lighter, high-speed, two-stroke sport models. Thus, the recent rise of variety in motorcycles resembles the technological development in aircraft, since in both cases, the rise in variety relates to the wider scope of services the technology can supply in the course of time.

Summarising, the changes in variety are related to the extent to which innovation can increase the range of services of a technology. In the history of aircraft, this range of services has been increasingly steadily and in various dimensions. In the history of motorcycles, the trend is less clear, but clearly increasing in the latter stage of development. In helicopter technology, technological change did not increase the range of services since inter-technological competition with aircraft technology limited the commercial possibilities of high-performance helicopters.

5.2. Microcomputers

The change in variety of microcomputers in Fig. 7 cannot be explained in relation to the changes in the range of services. Microcomputers were created as a niche but have become a very large market. The range of services that microcomputers are technically capable to supply, has increased rapidly as the speed and memory performance have risen at fast rates. However, the decreasing trend in variety suggests that, contrary to aircraft and motorcycles, the degree of differentiation has actually decreased. Thus, in the case of microcomputers, we do not observe a positive relation between scope of services and variety.

One particular feature of computers is a rate of change in performance, sometimes described as Moore's law, which is about an order of magnitude greater than that of any other technology. Another important feature of microcomputer industry concerns the very rapid convergence of most manufacturers on some features, such as the MS-DOS operating system or the generalised inclusion of hard-disk, CD-ROM etc. These standardisations relate to the presence of network externalities, since the exchange of electronic information requires compatibility among users. The emergence of technical standards can thus be expected to decrease variety ŽArthur, 1989 ..

Thus what seems to have characterised the evolution of microcomputers is the combination of an extremely rapid rate of technological change and of an extremely rapid rate of standardisation. The result of all this has been that the performance of all microcomputers, even the bottom-of-the-range microcomputers, has improved enormously. The lower end of the market continuously disappears as rapid technical change decreases the competitiveness of low-performance product models. Importantly, to purchase a high-performance micro-computer is not a luxury, but a necessity in consequence of the complementarity between the hardware and the software. New software allows users to benefit from services that are entirely unavailable by means of the older software, but that require high-performance computers since these cannot be run on the older computers. For example, Internet can only be accessed by means of computers having a minimum configuration of processor, memory, disk drive, etc. Thus, there is a very high rate of induced obsolescence that renders hardware unusable long before it is physically worn out.

The results can thus be explained only by making reference to the demand for microcomputers. If consumers had no interest in purchasing high-performance computers, then producers could not keep offering them. The services accessible with new combinations of hardware and software come at a price comparable to that of previous vintages of hardware and software. In fact, the services accessible by means of the new hardware and software quickly become an important competitive advantage for firms. High-performance computers also serve a device for the continued participation in social networks for individuals who exchange electronic information. Thus, consumers' utility is sharply increased by purchasing higher performance microcomputers, while a strong disutility would be associated with purchasing older, lower performance microcomputers, even if they were available at a lower price. The range of services does not increase, because maximum performance keeps growing while minimum performance increases at a comparable speed. Alternatively, we can say that low technology niches in microcomputers would be structurally unstable and would rapidly become extinct.

Niche theory, at least in the form in which it is formulated in biology, seems in this case incapable of explaining all the results obtained in this paper. We can observe that an important difference between aircraft and microcomputers is that, while the upper bound of the services performed increases rapidly in both cases, although much more rapidly in the case of microcomputers, the cost at which such services become available falls rapidly in the case of microcomputers. Two variables are then determining the possibility of differentiation and thus of variety growth. These are the range of services performed and the range of prices at which such services are supplied. In the case of aircraft the range of prices increases rapidly with the range of services provided as evidenced by the decrease in the number of high-performance models introduced on the market, while in the case of microcomputers the prices per unit of performance fall very rapidly.

The determinant of variety that we can consider is the ratio of the range of prices to the range of services performed. If this ratio increases we can expect differentiation and thus variety to grow. On the other hand, if the ratio of the range of prices to the range of services falls, we can expect de-differentiation and thus variety to fall. Niche theory has to be modified in order to be adapted to economic analysis. The nature of this modification is understandable when we bear in mind that the resources considered by biologists as the determinants of the number of niches are given, e.g., seeds of different sizes that relate to beaks of different sizes. In contrast, the services provided by a product technology are created at a cost, and such cost needs to be added to the range of services as a further determinant of variety growth. Of course, for the moment this cannot be more than a hypothesis, because we do not have the price data that would allow us to test such a hypothesis. It constitutes, however, an example that biological theories, while they can be useful for asking new questions about economic systems, cannot be expected to provide biological answers to economic problems.

Before concluding, it must be pointed out that the results we obtain for microcomputers might be partly due to the nature of our data. The differentiation of the software available seems to be increasing as a consequence of the increasing number of applications of computer technology. Since our data concentrate on hardware features, they obviously underestimate this increasing variety. It may well be the case that the convergence on a dominant design ŽMSDOSq, CDROM coupled with sharp reductions in. the costs of computing, has made it possible for related technologies to emerge. The growing range of both software and of other IT based technologies Že.g., cellular phones, pagers, etc. is an example of. this trend.

Summarising, we started by trying to explain the relative change of variety of aircraft with respect to helicopters by means of niche theory, a theory of biological origin. While this theory could explain the differences in the evolution of aircraft compared to helicopters, and to a lesser extent the evolution of motorcycles, it was subsequently unable to explain the case of microcomputers. We then proposed to modify niche theory by introducing the range of product prices in addition to the range of services performed. This extended version of niche theory can in principle explain our results, although we are for the moment unable to do a complete test of it due to the unavailability of price data for all technologies. This is a further example that biological theories cannot be used unchanged in economics, but that they need to be adapted.

6. Summary and conclusions

In this paper, we described two different measures of variety, and reported the results of the application of the two measures to aircraft, helicopters, motorcycles and microcomputers. The need for the two measures of variety that we presented in this paper arose in order to test a series of theoretical propositions about the role of qualitative change in economic development. The results show important differences in the behaviour of the four technologies. In two cases, aircraft and motorcycles, there is a general increase in variety, while in the other two cases, helicopters and microcomputers, variety falls. A comparison between aircraft and helicopters shows that the much wider range of services provided by aircraft allows for the creation of many niches while the narrow range of services provided by helicopters constitutes a niche within which further subdivision is not possible. Microcomputers, while being a technology in which the range of services performed has increased very rapidly, are characterised by a very high rate of cost reductions and by strong demand inducements to purchase high-performance models.

This combination, determined by the complementarity of hardware and software and by the strong disutility of remaining behind, induces a very rapid obsolescence of lower performance microcomputers, thus eliminating the lower part of the range of services.

The width of the range of services provided by the technology thus constitutes an important determinant of technological variety. Whether such range is already wide at the birth of the technology or whether it becomes wide due to a high rate of growth, such a wide range provides the analogue of a biological habitat into which a large number of niches can be created, thus raising the variety of the system. However, in presence of a rapidly growing performance, the range of services does not necessarily increase if sharp reductions in costs remove the lower range of services.

Our results have also 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 can be considered a technological division of labour, which originated historically as each design established itself in a niche in which it had a comparative advantage. Moreover, even in a technology, which does not subdivide itself, several designs may co-exist, with one of them being statistically dominant, that is being embodied in the majority of the models sold. The multiple surviving designs, whatever the number of models in which they are embodied, specialise in supplying those services in which they have a comparative advantage.

Our discussion suggests a number of directions in which future research can be pursued. First, confirmation of the determinants of variety discussed in this paper is required. This involves further empirical analysis of these and of other technologies. Second, the factors determining the growth of variety discussed here can be incorporated in simulation models of technological evolution and of firm behaviour. Third, at a higher level of aggregation, the variety measures can be used to study the relationships between variety growth on the one hand and output growth, employment growth and trade growth on the other hand.

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Appendix A. Description of the data

Aircraft

Number of observations: 731

Time span: 1913–1984

Sources

Jane's 1978Ž . *Jane's Encyclopedia of AÕiation* ŽLondon: Jane's Publishing. Jane's 1989Ž . *Jane's Encyclopedia of AÕiation* ŽLondon: Studio Editions.

Discrete Õariables classes within brackets( )

Engine type	ŽPiston propeller, Turboprop, Turbojet, Turbofan, Rocketmotor.
Number of engines	ŽOne, Two, Three, Four, Six, Eight, Twelve.
Wing type	ŽStraight, Delta, Swept, Variable swept.
Number of wings	ŽMonoplane, Biplane, Triplane.
Number of tails	ŽOne, Two.
Number of booms	ŽOne, Two, Three.

Continuous Õariables

Engine power kWŽ .
Wingspan mŽ .
Length mŽ .
Maximum take-off weight kgŽ.
Maximum speed kmŽ rh.
Range kmŽ.

Helicopters

Number of observations: 144
Time span: 1940–1983

Sources

Jane's 1978Ž . *Jane's Encyclopedia of AÕiation* ŽLondon: Jane's Publishing. Jane's 1989Ž . *Jane's Encyclopedia of AÕiation* ŽLondon: Studio Editions.

Discrete Õariables classes within brackets( )

Engine type	ŽPiston, Piston turbo, Ramjet, Gas generator, Turboshaft.
Number of engines	ŽOne, Two, Three.
Number of blades	ŽTwo, Three, Four, Five, Six, Seven, Eight.
Number of shafts	ŽOne, Two.

Number of rotors per shaft One, TwoŽ .

Continuous Õariables Engine power kWŽ .
Rotor diameter mŽ .
Length mŽ .
Maximum take-off weight kgŽ.
Maximum speed kmŽ rh.
Range kmŽ.

Motorcycles

Number of observations: 80
Time span: 1911–1996

Source

Brown 1996Ž.

Discrete Õariables classes within brackets( )

Engine type	ŽTwo-stroke, Four-stroke.
Number of cylinders	ŽOne, Two, Three, Four, Six.
Cooling system	ŽBy air, By water, By oil.

Continuous Õariables Volume cmŽ ^{3}.
Power hpŽ.
Weight kgŽ.
Maximum speed kmŽ rh.

Microcomputers

Number of observations: 4917
Time span: 1983, 1984, 1988, 1992–1997

Source

What PC? Vols. 1983, 1984, 1988, 1992–1997

Discrete Õariables classes within brackets( )

Processor type ŽZ80, Z80a, Z80 twin, Mn602, NSC800, Z800, 6809r6809e, Z80q6502, 2)Z80a, Z80bq8088, 6809q6800e, 2)8085r2)8085e, 8085q8083, 8088q8087, 8088q8086, 6301, 6502, 6509, 6510, 6800, 6809, 68000, 8083, 8085-8085a-8085a2, 8086, 8088, 9900, 286, 386SX compatible, 386DX, 386 SL, 486, 486SX 2 , 486DX,Ž . 486DX2, 486DX4, 486SLC 2 ,Ž . 486SL 2 , 486SLE, 486SL2,Ž . 486SXL, IntelV25, PENTIUM, PENTIUMPRO, ARN, AMD, NECV20, ThompsonDX2, ThompsonDX4, 586, IBM6x86, IBM686, IBMBL, DellLatitude, NexgenNx586, SunSpark1, SunSpark2, V30.

Operating system ŽDOS, CPM, DOS and Others, CPM and Others, Others, Own System, Cassette, DOS and CPM, DOS or Windows3.1, DOS and Windows3.11, DOS or Win3.11 or Win95, System7.5, System7.5 and Win95, Win95, DOS and Win_for_workgroups, Win3.11 and Win_for_workgroups, DR DOS5, DR DOS6, IBM DOS, PC DOS.

RS232 ports ŽOne, Two, Three, Four.

Monitor ŽYes, No.

Colour display ŽYes, No.

CD-ROM ŽYes, No. Portable ŽYes, No.

Continuous Õariables

Speed MHzŽ .

RAM kilobitsŽ.

Harddisc memory kilobitsŽ.

Floppy memory kilobitsŽ.

Appendix B. Years for each period

Aircraft 731 obser(Õations; 43 periods of 17 obserÕations)

1. 1913–1916	2. 1916–1917	3. 1917	4. 1917–1919
5. 1919–1923	6. 1923–1926	7. 1926–1928	8. 1928–1929
9. 1929–1931	10. 1931–1932	11. 1932–1933	12. 1933–1934
13. 1934–1935	14. 1935	15. 1935–1937	16. 1937
17. 1937–1938	18. 1938–1939	19. 1939	20. 1939–1940
21. 1940–1941	22. 1941–1942	23. 1942–1943	24. 1943–1944
25. 1944–1945	26. 1945–1948	27. 1948–1950	28. 1950–1953
29. 1953–1954	30. 1954–1956	31. 1956–1958	32. 1958–1959
33. 1959–1962	34. 1962–1963	35. 1963–1965	36. 1965–1967
37. 1967–1968	38. 1968–1970	39. 1970–1971	40. 1971–1974
41. 1974–1976	42. 1976–1978	43. 1978–1984	

Helicopters 144 obser(Õations; 12 periods of 12 obserÕations)

1. 1940–1954	2. 1954–1957	3. 1957–1959	4. 1959–1961
5. 1961–1963	6. 1963–1966	7. 1966–1967	8. 1967–1971
9. 1971–1974	10. 1974–1978	11. 1978–1981	12. 1981–1983

Motorcycles 80 obser(Õations; 8 periods of 10 obserÕations)

1. 1911–1937	2. 1938–1955	3. 1956–1961	4. 1961–1968
5. 1969–1975	6. 1975–1982	7. 1983–1993	8. 1994–1996

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